Alaska Arctic Coastal Plain Gravel Pad Hydrology: Impacts to Dismantlement Removal and Restoration Operations;

A Study on the Human – Hydrology Relationship in Arctic Environments

By

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Abstract

To guard against thawing permafrost and associated thaw subsidence, the oil facilities in the Arctic are constructed on gravel pads placed on top of the existing arctic tundra, however the impacts of this infrastructure to the sensitive hydrology are not fully understood. Production in some of the older fields is on the decline; however oil exploration in the Arctic Coastal Plain is resulting in the discovery and development of new reserves. In the coming years, old sites will need to be decommissioned as production transitions to new sites. New facilities will also need to be designed and constructed.

Oil companies in Alaska have historically conducted operations under leases issued through the Alaska Department of Natural Resources. The leases stipulate that once resource extraction operations are completed, the facilities must be decommissioned and the sites restored, however they are often vague in their requirements and are variable in their specifics from lease to lease.

As the oil companies transition to the new sites, decisions must be made regarding what should be done with vacated gravel pads. The construction of gravel pads essentially destroys underlying arctic tundra. In undisturbed areas in the Arctic, the tundra itself creates an insulating layer that limits the seasonal thaw depth to around 0.5 m. Removal of this layer causes thaw depths to greatly increase impacting the stability of the ground and the hydrology of the surrounding area. Because of this impact, other possible restoration techniques are being considered, such as vegetating and leaving the pads in place.

Water movement is one of the major driving factors in the arctic contributing to permafrost degradation. Groundwater carries with it heat, which is transferred to the soil as the groundwater moves. Therefore, hydrology plays a major role in the stability of the arctic environment. This is especially relevant in areas where gravel pads exist. Gravel pads are anthropogenic structures that have significant water storage potential. Because of the unique conditions in the Arctic, pore-water flow through these gravel pads is not yet well understood.

The purpose of this study is to develop a more complete scientific understanding of the driving forces behind pad pore-water movement. This study expands on fieldwork from a prior hydrological field study conducted by others. The prior study is expanded through this work by developing an associated groundwater model to the gravel pad from the field study to examine the flow through it and the controlling factors for this flow. The study site used for this project is located in Prudhoe Bay and is the pad constructed for the very first production well in Prudhoe Bay in 1968.

This study demonstrates that it is the topography of the silt layer beneath the gravel pads that is the most significant factor controlling pad pore-water movement. The results from the modeling study will assist engineers and environmental scientists in better understanding the groundwater flow. This understanding will aid in the decommissioning and restoration process and help inform decision making in regards to the future of the existing pads. The results may also be used to inform the development of new infrastructure such that any new pads which are built may be constructed with their relationship to they local hydrology more in mind.

Table of Contents

List of Figures

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List of Tables

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List of Appendices

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Preface

"Whoever drinks of the water that I will give him shall never thirst; the water that I will give him will become in him a well of water springing up to eternal life."

- Jesus of Nazareth

When speaking to a woman at a well who provided him a drink nearly two thousand years ago, a Jewish teacher named Jesus of Nazareth spoke these words. This quote has hung on the wall in my office for most of the time that I have been working on my research and it has framed the way that I think about my work and what I am studying. As a disciple of Jesus, I strive to see the significance of my work no matter what it is, in the context and light of my faith. I have grown to believe that God created men and women to be stewards of the planet he created and care for the world he placed us in. Through engineering we harness the natural forces of the world, and through engineering we also manage and care for our world.

Jesus associated water and life together, and as I have studied it, I have gained a deeper appreciation for that association. Nearly everything we use on a daily basis water went into, either for manufacture or transportation. Water is involved in nearly every aspect of our lives yet it flows silently behind the scenes often unnoticed in our day to day rhythms and patterns of life. The water resources of the earth have historically been one of the most vital to society and yet most mismanaged resources on the planet. Water however, because it is dynamic, is inherently more difficult to manage than traditional resources such as precious metals or timber forests. Because it is naturally replenishing, water is often falsely perceived as being an inexhaustible resource which often leads to over taxation of the limited supply of it in any given aquifer or watershed.

There are many problems in the world related to water and I imagine that I will not even begin to solve most of them. I do believe however, that my research contributes in some small way to helping us better understand and manage the water resources of Alaska. Having grown up in Alaska and lived here for the majority of my life, this is a place which I call home and care about personally. I want to see the water resources of my State well managed for the benefit of all Alaskans and I have confidence that my research helps achieve this goal. Water resource issues in Alaska will only become more significant as polar sea ice continues to melt and the climate continues to warm.

When I first started my masters program, I wasn't sure which discipline I really wanted to focus my research in. I selected the Water Resources program because of an opportunity that opened up for me to do research in that area doing groundwater modeling and working on this project. As I have moved through the program however, water has over time become something not only that I study, but something that is deeply and personally meaningful to me and something which has shaped fundamentally who I am. The hydrology of the Arctic Coastal Plain is fascinating and extremely complex. Although it has been difficult at times, I have thoroughly enjoyed working on this study, and am proud of the work I have accomplished. It has been a rewarding experience which I am very thankful that God has given me the opportunity to have.

Acknowledgments

I am truly grateful for the individuals who have helped support me through my research process to bring me to the completion of my degree, farther than I ever thought I might go. The most influential person in bringing me here is Dr. Dave Barnes my research adviser and committee chair. I first met Dave when I was in the pre-engineering program at the University of Alaska Southeast and he came to present his dust research to us. Since then, Dave has been my adviser in both my undergraduate and graduate programs and has encouraged and supported me the entire way. I am extremely grateful for his passion to serve people and pour into and grow and develop his students beneath him. Dave has set an extremely high bar for me to live up to, but he has also given me the push and the tools necessary to achieve that high bar. Thank you Dave for coaching and mentoring me as I have pursued my education.

I would also like to thank some of the other graduate students who have helped encourage and guide me as well as we have traveled this journey together. I am grateful to (the now Dr.) Zhili Quan who has shared an office with me during my time here and has on multiple occasions commiserated with me when my model simply would not run and also helped provide modeling tips and advice to me when I needed them. I would also like to extend thanks to Ravi Paturi who is also in the Water Resources program with me. Thank you Ravi for your friendship to me while I've been here. I have very much enjoyed working with you as a TA and just bouncing random ideas off you when I've had them.

Finally I would like to extend my appreciation to my full committee, Dr. Barnes, Dr. Stuefer, and Dr. Shur who have each helped me and guided me in their own way. In particular I would like to thank Dr. Stuefer for reviewing the surface water related portions of my study and for telling me to just buckle down and do my work when I needed to hear it.

This has been a long but rewarding journey and I am very thankful that have had the chance to take it. The University of Alaska Fairbanks, the College of Engineering and Mines, and the Water and Environmental Research Center have provided a very positive environment and atmosphere to work in. They are staffed by excellent, dedicated and committed individuals who go above and beyond to help those in their programs achieve their goals.

Dedication

For my family:

My parents Kevin and Theresa Miller and my Brother David.

Dad:

Thank you for supporting me and helping me financially to survive my program. Thank you for giving me advice and helping coach me through life to bring me to this point.

Mom:

Thank you for supporting me and praying for me as I have worked. Thank you also for beginning my education process homeschooling me and helping propel me into the engineering program in high school which eventually has lead me here.

David:

Although we have taken different paths, I am proud of the path you have taken. I pray that you can be proud of the accomplishments you have achieved on your path just as I am of mine.

Chapter 1 Introduction

The infrastructure developments constructed for oil exploration and production in the Arctic Coastal Plain of Alaska over the past five decades, have resulted in the placement of roughly 92 million cubic meters of imported gravel material onto the surface of the arctic tundra *(Alaska Department of Natural Resources, 2018).* There are still many unanswered questions regarding the impact this placed gravel has had to the sensitive hydrology of the Arctic Coastal Plain. Coastal Plain tundra is extremely thermally sensitive because the active layer is very shallow. Additions of heat to the system often result in degradation of permafrost and frozen soils causing thermokarsting. Building on gravel pads helps create a thermally insulating separation of non-frost susceptible material between the surface infrastructure and the native soils protecting against thaw subsidence and thermokarsting. One important yet not well understood component of the Arctic Coastal Plain hydrology is the pore-water movement through the gravel pads on which the infrastructure is built. Therefore, it is the purpose of this study to develop our understanding of this aspect of the gravel's impacts on arctic hydrology.

On the Coastal Plain of Alaska the environment is highly ecologically and hydrologically sensitive for a number of different reasons. Firstly, the huge annual swings in temperature create drastic hydrological impacts. Each year over the course of the winter water is stored in snow packs and ice and then in the spring during breakup the major annual hydrologic outflow occurs as the snow melts.

Secondly, the Coastal Plain is primarily an Arctic desert. One study on Arctic coastal hydrologic runoff (Stuefer et al. 2017) cites the Coastal Plain precipitation to vary between 140 mm/yr near the ocean to 340 mm/yr closer to the mountains. Because of the extremely low amounts of precipitation and very flat topography on the Coastal Plain, any small amount of water in the system in any given watershed contributes a very large amount to its overall hydrological character.

Thirdly, the Coastal Plain of Alaska is nearly completely underlain by permafrost. Permafrost plays a significant role in the hydrology of the Arctic Coastal Plain because it largely impedes water flow acting as an aquitard and creating a confining soil layer. In many places on the Coastal Plain, the active layer can be very shallow below the ground surface causing large amounts of ponding water in what would otherwise be an extremely arid region.

1.1 Oil Facility Dismantlement Removal and Restoration (DR&R)

Hydrologic considerations must be taken into account when developing any sort of infrastructure in the Arctic. Oil companies in Coastal Plain regions have build their facilities on gravel pads overlaying the Arctic tundra to protect it from thaw. At some point the northern Alaskan oil reserves will become unprofitable and the existing infrastructure constructed on the Arctic Coastal Plain must be decommissioned and operations relocated to new oil fields. Under the leases by which the oil companies operate, when decommissioning occurs, dismantlement and removal of the facilities and restoration of the land must take place (DR&R).

As the oil companies move more towards transitioning to new locations, DR&R operations will only become more and more significant over time. When the time comes for the transition away from the existing facilities which is expected in the very near future, decisions must be made regarding what to do with the old facilities. The largest piece of infrastructure which must be decomissioned is the gravel pads on which the facilities are constructed. Therefore perhaps the most significant decision they will have to make in the DR&R process will be what to do with the pads themselves. A number of options are being considered at present. One of the simplest options being examined is simply to leave the pads in place as they are. If this is done, they will gradually erode away due to lack of maintenance and rotational failure at the edges of the gravel pad structures. Another option is revegetation. The growing season in the Arctic Coastal Plain is extremely short and only limited plant species can survive the harsh arctic climate. Therefore this solution is not without its own technical challenges. Finally, oil companies are exploring the idea of removing either a portion of or all of the gravel of the pads at the facilities. This action could result in significant changes to the surface topography and consequently the arctic environment as well.

When exploring DR&R alternatives for the pads, among other considerations, the hydrology of the gravel pads must be understood since the hydrology will play a large role in the environmental impacts of the DR&R operations. Because of the potential environmental impacts of DR&R, our understanding of the hydrology must be developed before the pads can be properly decommissioned or pads in new areas constructed. Simply removing the gravel off of the face of the tundra could very well result in significant harm to the environment by causing thermokarsting resulting in the formation of new water bodies. In addition, some of the pads are contaminated with petroleum and other industrial chemicals that can migrate into tundra environments surrounding the gravel pads and be transported via Coastal Plain water movement. Therefore it is crucial to understand the hydrology to avoid unnecessary frozen soil degradation or the spread of chemical contamination into sensitive tundra environments.

1.2 Study Objectives

To develop a more specific scientific understanding of gravel pad hydrology in this study, a computer model has been constructed using the USGS software MODFLOW-2005 *(Harbaugh, 2005)* of pad pore-water movement through the very first pad constructed on the Arctic Coastal Plain in 1968. By modeling the facility we can gain more specific and useful scientific insights into the hydrology of gravel pad structures constructed on the arctic tundra. Although the specifics of the facility modeled in this study obviously may not apply to all pads in the Arctic, we can learn more about the general principles of pad pore-water movement, which will help us understand the impacts of gravel pads to arctic hydrology. The two primary study objectives are:

Study Objective #1:

Quantify the hydrology and hydraulic parameters of the Crude Oil Topping Unit (COTU) pad,

Study Objective #2:

Explore the potential hydrological impacts of DR&R alternatives.

The first main objective, examining the effects of various modeled hydrological properties and their influences on the gravel pad hydrology, was chosen to develop a more complete understanding of the pad-pore-water movement. It was also at the water balance of hydrologic inputs and outputs to the system to understand the volume of water moving through the pad. Modeling also allows for the detailed examination of the hydrologic aspects of pad pore-water movement through gravel pads that a field study cannot achieve.

The second objective the model was intended for, understanding the hydrologic impacts of various remedial strategies that may be employed during DR&R activities, was chosen to focus this research more directly towards current technical concerns and challenges oil companies operating in the Arctic are facing. This modeling study quantifies the amount of water flowing through the facility; an understanding useful to decisions that must be made on leaving gravel pads in place or removing some portion of the gravel at the end of their service life.

1.3 Study Summary

A field study conducted by Barnes (2014) is the primary source of data for this study. The pad in the study is referred to as the Crude Oil Topping Unit (COTU) and is currently operated by British Petroleum. The pad was originally constructed by Atlantic Richfield and Humble Oil (ARCO) in 1968 when oil production in Prudhoe Bay first began. The facility was acquired by BP when the two companies merged in 2000.

The effect of precipitation on pad hydrology can be explored through the use of the model. It was originally hypothesized in the Barnes (2014) study that during precipitation events water would be stored in the pad which would otherwise be surface runoff which would have a significant impact to the pad hydrology. In this study the model has been used to look at how changes in precipitation affect the pad pore-water flow patterns. In addition to precipitation, the hydrologic conditions of the surrounding watershed and their relationship to the hydrology within the pad itself were able to be explored with the model. By modifying the model edge boundary conditions more can be learned about what the conditions just off the pad may be like and what relationship they may have with the hydrology inside the pad. Examining this relationship is accomplished by comparing the modeled pad edge conditions to observed data from the Barnes (2014) field study. Finally, one of the major findings of the Barnes (2014) study was that the flow patterns are strongly influenced by the subsurface silt topography. The model has revealed more about the relationship between the topography of the subsurface silt below the gravel pad as well as the permafrost, and the flow patterns through the gravel pad.

It is of one the goals of this study to further develop a scientific understanding of the hydrology of Arctic Coastal Plain gravel pads which information will be useful to DR&R decision makers both in the oil companies and in the Alaska State government as well as to other parties such as the Alaska Native Corporations. There will most likely not be a universal DR&R solution that can be applied at every facility. Despite this, many of the facilities will have similar considerations and concerns regarding the environmental impacts of the DR&R process even if the specifics vary from site to site. It is the intent of this study to examine one pad in detail, and then identify some of the common hydrological similarities in general between the gravel pad structures in regards to the issues they will face with the decommissioning. It is not the purpose of this study to make specific or official engineering recommendations on how to decommission the facilities but rather to supply supporting information to all parties for whom it may be relevant.

To develop our understanding of the hydrology of the gravel pad structures in the Arctic, a historical survey has been conducted examining the development of the gravel pads over time and their relationship to the hydrology of their environment. The intent of the historical survey is to develop our understanding of the broader sociological and economic context into which the gravel pad hydrology fits. Examining the human-nature relationship in regards to hydrology of the Arctic Coastal Plain over the development period of the oil infrastructure will give us a more complete picture of current industrial practices and activities taking place there today. The relationship between Arctic Coastal Plain hydrology and industrial activity will become particularly relevant as the warming Arctic climate continues to affect the Coastal Plain environment as well.

1.4 Summary of Key Findings

The modeling study revealed a number of interesting features of the gravel pad hydrology. Contrary to the initial hypothesis of the Barnes (2014) study regarding the precipitation, the model showed that the precipitation effects on the pad were nearly negligible in their overall impact to the hydrological character of the system. The Coastal Plain precipitation is simply too low to have a significant impact on the water balance of the system. Of the inputs and outputs to the model, it was water that was already stored within the pad entering the modeled area that had the most significant effect on the water balance into the model. The water exited the model primarily through the edges of the gravel pad into the surrounding tundra ponds just off the edges of the pad. Because the tundra ponds around the pad edges in the model were at lower elevations than the water table within the gravel pad, their effect on the system was primarily to create a hydraulic gradient that removed water out of the pad rather than contributing water to it.

Overall, the most significant controlling influence to the system the model revealed was the topography of the underlying silt beneath the gravel pad on which it was built. Because of the shallow active layer, the silt layer becomes quickly saturated by the water in the system. Once the silt has been saturated, because of the lower hydraulic conductivity of the silt than the gravel that is placed on the tundra, the flow patterns follow the topographical character of the tundra surface that existed prior to the building of the gravel pad. The original subsurface silt depressions create a flow channeling effect by which the water moves through the deposited gravel, filling depressions and preferentially flowing around the high points of the silt topography. The silt topography therefore influences the water movement through the gravel pad more strongly than any other factor in the system.

Chapter 2 Historical and Legal Overview of Northern Alaska Oil Developments

In 1968, a major oil discovery, in fact the largest one in the US at the time, was discovered near Deadhorse Alaska by a joint venture exploration of Atlantic Richfield and Humble Oil *(Orians et al., 2003).* Shortly thereafter, the first oil production facility on the Arctic Coastal Plain was constructed on this find. Within a decade, in 1977, the 800 mile long Trans-Alaska Pipeline (TAPS) was completed allowing for the flow of oil from Prudhoe Bay to port in Valzez, Alaska *(Hill and Yeager, 2002).* After its completion, numerous oil production sites began to grow in other locations across the Coastal Plain of Alaska.

In the several decades since that period, much of the easy to access oil has been produced *(Hill and Yeager, 2002).* There is still a substantial amount of oil remaining, however it is more viscous making it more difficult and expensive to produce. In recent years, the previously restricted 1002 Area along the northern coastline of the Arctic National Wildlife Refuge (ANWR), on which congress had previously deferred a decision, *(Comay et al., 2018)* has become open for development of oil. In addition the Bureau of Land Management has continued to slowly issue leases opening up the National Petroleum Reserve – Alaska along the northwestern coastline of Alaska for development *(Oil and Gas Technical Report, 2014).* Due to the declining Trans-Alaska Pipeline (TAPS) flows, in the coming years oil companies will begin to decommission the existing sites they occupy and transition to the new areas for oil production *(Comay et al., 2018).* The oil production facilities on the Coastal Plain of Alaska are constructed on gravel pads placed onto the Arctic tundra surface. When these facilities are closed down, then their leases require that DR&R operations be conducted. As part of the DR&R, something must be done with the gravel pads on which the facilities were built.

Currently the oil production sites in Alaska are operated under leases issued to the oil companies by the Alaska State legislature through the Department of Natural Resources. Although the leases are issued individually to corporations, they are typically legally grouped together in large zones referred to as “units”. Each unit has a legal agreement that is structured similarly to those issued for individual leases. The unit agreement is for the entire unit as a whole rather than for a specific lease within it. Although each unit may have multiple invested oil corporations who all hold leases within it, there is a single primary operating company who’s responsibility it is to manage the overall oil production activities within the leases that make up that unit *(Hill and Yeager, 2002).*

The requirements for dismantlement, removal, and restoration (DR&R) in the lease agreements are generally non specific. As a result the responsibility for DR&R within the unit falls upon the primary unit operator regardless of which other corporations may hold leases in it. No DR&R activity is required until the unit agreement is terminated *(Hill and Yeager, 2002).* At the termination of the unit agreement, the management of the land reverts back to the State of Alaska, which is the primary owner. Ultimately, the State of Alaska needs to make a decision as to what is to be done with these pads once they are vacated before any of the oil companies will spend money on DR&R operations. Current State DR&R requirements are more general and less specific allowing for various DR&R alternatives to be explored *(Hill and Yeager, 2002).*

2.1 Early Natural Resources Legal Management

The development of the laws governing Alaska’s natural resources (including petroleum) can be traced all the way back to the purchase of Alaska from Russia. When purchased from Russia, Alaska was adopted into the union as a US Territory in 1867. The US congress passed the General Mining Act in 1872 shortly after Alaska’s incorporation into the United States *(30 U.S.C. §§ 22-42).* As a newly adopted US territory, Alaskan lands and natural resources (including oil although at that time yet undiscovered), fell under the governance of the General Mining Act as soon as it was passed. The

General Mining Act allowed for the establishment of mining claims and prospecting on public lands within the United States. The General Mining Act reads:

> *"SEC. 2319. All valuable mineral deposits in lands belonging to the United States, both surveyed and unsurveyed, are hereby declared to be free and open to exploration and purchase, and the lands in which they are found to occupation and purchase, by citizens of the United States and those who have declared their intention to become such, under regulations prescribed by law, and according to the local customs or rules of miners in the several mining-districts, so far as the same are applicable and not inconsistent with the laws of the United States."*

In 1920 the laws governing Alaskan natural resources changed again when US congress passed the Mineral Leasing Act which allowed for mining claims in US lands to be leased out opening them for resource development. *(30 U.S.C. § 181 et. seq.)* The Mineral Leasing Act was significant because it codified the process for development of federally managed lands that were not covered under the General Mining Act. Oil and gas were specifically included in the Minerals Leasing Act in section 13.

> *"Sec.13. That the Secretary of the Interior is hereby authorized, under such necessary and proper rules and regulations as he may prescribe, to grant to any applicant qualified under this Act a prospecting permit, which shall give the exclusive right, for a period not exceeding two year, to prospect for oil or gas upon not to exceed two thousand five hundred and sixty acres of land wherein such deposits belong to the United States and are not within any known geological structure of the producing oil and gas field upon condition that the permittee shall begin drilling operations within six months from the date of the permit, and shall, within one year from and after the date of permit, drill one or more wells for oil or gas to a depth not less than two thousand feet unless valuable deposits of oil or gas shall be sooner discovered."*

In 1909 US president Taft by executive order set aside large portions of US lands creating the first national petroleum reserve for the US Navy *(Getches, 1982)* The US congress ratified this in 1910 passing the Pickett Act which granted the president the authority to reserve US lands for this purpose including the territory of Alaska (43 *U.S.C. § 141 Stat. 847).* (This was later repealed by congress in 1976.) In 1923 president Harding using this authority again, created the Naval Petroleum Reserve No. 4 which set aside 37,000 square-miles, roughly 38 % of the Northwestern portion of Alaska for petroleum development for the US Navy. *(Oil and Gas Technical Report, 2014)*

In 1944, the US Navy as part of the war effort started a petroleum exploration program (PET-4) for the Naval Petroleum Reserve No. 4 *(Reed, 1958).* PET-4 took place from 1943 – 1953. During the PET-4 surveys, oil reserves were discovered at Umiat, Cape Simpson and Fish Creek. Natural gas reserves were also discovered as well. As a result of the survey, the South Barrow gas field was developed in 1949 *(Oil and Gas Technical Report, 2014).* No other findings from PET-4 were determined to be commercially viable for development at the time of discovery. They were never developed because the infrastructure required to develop them was not yet in place. By the time that the reserves were identified and could have been developed, WWII was largely over and the urgency of the need for development was past. *(Orians et al., 2003)* The PET-4 exploration program continued however after the war until 1953 *(Reed, 1958).* The Naval Petroleum Reserve No. 4 would be in 1976 transferred to the US Bureau of Land Management underneath the Department of the Interior and renamed the National Petroleum Reserve Alaska (NPRA) *(P.L. 94-258).*

2.2 Statehood and Natural Resources

The achievement of the status of statehood had a significant impact on natural resource management for the State of Alaska. Prior to the establishment of statehood, Alaskan land and natural resources had been managed underneath the General Mining Act and the Mineral Leasing Act by the Federal Government through the Bureau of Land Management. However, at the establishment of statehood the State of Alaska through its constitution adopted ownership responsibility and management of the State's land and natural resources including its oil. The Alaska State Constitution Article VIII codifies the process of natural resource management in the State.

> *"Sec.12. The legislature shall provide for the issuance, types and terms of leases for coal, oil, gas, oil shale, sodium, phosphate, potash, sulfur, pumice, and other minerals as may be prescribed by law. Leases and permits giving the exclusive right of exploration for these minerals for specific periods and areas, subject to reasonable concurrent exploration as to different classes of minerals, may be authorized by law. Like leases and permits giving the exclusive right of prospecting by geophysical, geochemical, and similar methods for all minerals may also be authorized by law."*

Although according to the State Constitution ownership of all of the land and minerals within the State boundaries legally belong to the State of Alaska as a sovereign entity, the State government only claimed a portion of it's lands for State management leaving much of its land such as the Naval Petroleum Reserve No. 4 to continue to be Federally managed even after Statehood. In 1964, the State of Alaska claimed responsibility for a roughly 100 mile wide stretch of the Arctic Coastal Plain opening it up for oil development as it was believed to have substantial oil potential in the wake of the exploratory findings of the PET-4 surveys *(Hill and Yeager, 2002)*. At present the majority of oil developments exist within this 100 mile swath State managed land. It was this State initiated development which led to the discovery of the Prudhoe Bay strike four years later in 1968.

The actual management and regulation of the development of the petroleum on the Arctic Coastal Plain is complex and involves multiple levels of government from the local municipal through the federal. At the municipal level, the North Slope Borough and the Native Corporations have zoning authority on all non-federally managed lands *(Hill and Yeager, 2002).* Developments on the Coastal Plain are split up into development areas called units. Each unit is run by a primary operating corporation referred to as the unit operator. Although the unit operator is the primary responsible party for the activities within the unit, there may be multiple invested corporations within each unit that share the costs and profits of the operations.

The permitting of the operations within the units is overseen by the State through the Alaska Oil and Gas Conservation Commission (AOGCC). The State of Alaska at statehood also established the Department of Natural Resources (ADNR) to promote development of the natural resources of the State. The State legislature delegates its constitutional leasing authority of land and mineral rights to the ADNR. It is these two agencies, AOGCC and ADNR, that have the final authority for enforcing DR&R requirements *(Hill and Yeager, 2002).* The State of Alaska also established the Department of Environmental Conservation (ADEC) to regulate management of the environmental impacts of industrial development. Likewise the Department of Fish and Game was established to manage wildlife species for both subsistence and recreational use. Each of these State agencies has a role in any development and management of the oil fields which takes place in the State.

At the Federal level, the US Army Corp of Engineers handles permitting of the development of any lands classified as wetlands or waters of the United States under section 404 of the Clean Water Act and section 10 of the Rivers and Harbors Act *(33 CFR – 323).* The law delegates to the Corps of Engineers permitting authority for placement of fill or dredged material in areas classified as Waters of the United States. In 1979 the Corp of Engineers asserted this authority to include wet and moist arctic tundra *(Hill and Yeager, 2002).* As a result, this law expanded their authority to require permitting for the development of the facilities on Alaska's Arctic Coastal Plain. Because the Coastal Plain is underlain by permafrost, a vast majority of the region can be classified as wetlands, so nearly all the developments across the Coastal Plain fall into this category *(Orians et al., 2003).* As of 2002, the Corp of Engineers had issued roughly 1,100 permits for the development of gravel pad structures since they adopted enforcement authority in 1979 *(Hill and Yeager, 2002).* The Corp of Engineers estimated that approximately half of the gravel pad structures laid down on the Arctic tundra were constructed prior to 1979 and therefore not permitted by them *(Hill and Yeager, 2002).*

Outside of the State managed lands in the center of the Coastal Plain, the US Department of the Interior (DOI) is responsible for federally managed lands. Underneath the DOI, the Bureau of Land Management manages the National Petroleum Reserve – Alaska (NPRA) to the west and the Arctic National Wildlife Refuge (ANWR) to the East is managed by the US Fish and Wildlife Service. *(Hill and Yeager, 2002).* Within the NPRA, the Bureau of Land Management, under Federal authority delegation holds leasing authority for development of the reserves of the NPRA *(Oil and Gas Technical Report, 2014).* The BLM issued its first lease within the NPRA in 1982 *(Oil and Gas Technical Report, 2014).* To date much of the NPRA has not yet been leased out, however the BLM continues to slowly open up the area for development. Although ANWR is managed by the Fish and Wildlife Service, the Department of the Interior under the direction of P.L. 115 – 97 delegated administration of the development program for the 1002 area to the Bureau of Land Management. Therefore, the BLM holds leasing authority for both the NPRA as well as the 1002 area of ANWR. The 1002 Area is the only portion of ANWR which is open for leasing. The Fish and Wildlife Service is not authorized to lease out any portion of the land *(Comay et al., 2018).* Figure 1 shows a map of the Federally managed lands in northern Alaska.

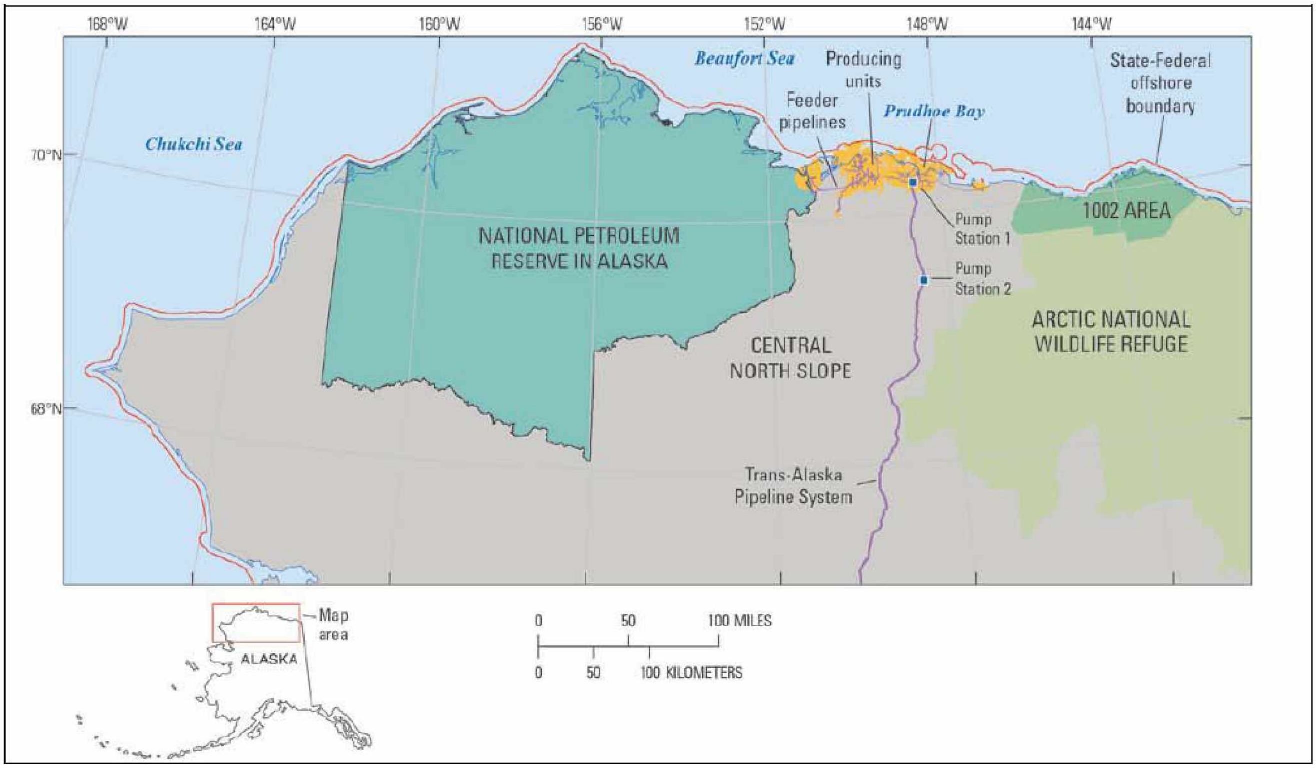

Figure 1: Northern Alaska Federally Managed Lands – Source: Comay et. al. (2018)

2.3 Oil Field Development and the Economic Boom of the 80's

The 1968 ARCO oil discovery at Prudhoe bay was the first of numerous oil reserves upon which facilities would be constructed all across the Coastal Plain of Alaska. Construction on the Trans-Alaska Pipeline System (TAPS) began in 1975 and it was completed in 1977. The opening of the TAPS permenantly changed the economy and the industry of the State of Alaska *(Hill and Yeager, 2002)*. With the opening of the pipeline, Alaska entered the globalized economy as a producer of oil. The oil industry would bring billions of dollars into the State economy, however it came at the cost of Alaska's economy becoming tied inseparably to the oil companies and the global oil market. For the Arctic Coastal Plain, it meant development of the vast reserves of oil in northern Alaska. The result of this development was the building of facilities on the sensitive arctic tundra forever changing the face of large areas in Arctic Alaska.

After the construction of TAPS, oil production in the State increased until it peaked in 1988 at roughly 2 million barrels of oil per day *(Hill and Yeager, 2002).* The majority of the surface gravel infrastructure developments were constructed prior to 1988 *(Orians et al., 2003).* After 1988 most of the core infrastructure required for oil operations was already in place and so the rate of development slowed down substantially *(Orians et al., 2003).* From 1988 onward, due primarily to most of the easily accessible oil within State lands being developed already, production of both oil and of infrastructure developments began to decrease *(Orians et al., 2003).* There is still oil in the Arctic Coastal Plain but within State lands it is becoming more difficult to access because it is in deeper and more isolated reserves. In addition, the lower viscosity oil which is more easily recoverable has largely been produced. These factors combine, resulting in increasing costs and decreasing profitability of production *(Hill and Yeager, 2002).* Eventually, when the profitability of production drops low enough, corporations decide to decommission their operations and undergo DR&R of their facilities. Already the oil companies have begun experimental DR&R operations at numerous small test sites. *(Oil and Gas Technical Report, 2014).*

As a result of increasing costs and decreasing profitability, interest in the oil reserves in Federally managed lands has increased substantially in recent years *(Oil and Gas Technical Report, 2014).* Within Federally managed lands, there is accessible oil within ANWR in the east and the NPRA in the west, that has not yet been recovered. ANWR has historically been restricted from development until the recent opening of the 1002 area. According to the USGS there is an estimated 7.7 billion barrels of recoverable oil within the 1002 area oil fields *(Comay et al., 2018).* The NPRA has been slowly opened up by the BLM however much of it is still undeveloped *(Oil and Gas Technical Report, 2014).* In recent years more exploratory drilling has taken place and discussion has taken place about further opening up of certain portions for development. Even with the development of Federally managed lands however, it is not anticipated that TAPS will return to its pre 1988 flow rates *(Hill and Yeager, 2002).*

2.4 Development of the ANWR 1002 Area

In 1980 after TAPS opened, to preserve portions of Alaskan wilderness, the US congress passed the Alaska National Interest Lands Conservation Act *(P.L. 96-487: ANILCA).* As part of this act was included Title X- Federal North Slope Lands Studies, Oil and Gas Leasing Program and Mineral Assessments. Within Title X, the Arctic National Wildlife Refuge (ANWR) was established as a region of northeastern Alaska not to be developed for the purpose of preservation of the land and for arctic wildlife species. *(P.L. 96-487 – Title X).*

A portion of the land set aside by ANILCA however, stretching along the northern Coastal Plain, congress deferred making a decision on because of a conflict between its value as hub of activity for caribou and polar bears and its potential for large oil reserves. This region has been designated Area 1002 after the section of the act in which it was established. The 1002 area spans approximately 1.5 million acres along the northern coastline above ANWR *(Comay et al., 2018).* According to ANILCA Title X, this portion of land could only be developed if authorized by an act of congress *(P.L. 96-487 – Title X).*

> *"SEC. 1003. Production of oil and gas from the Arctic National Wildlife Refuge is prohibited and no leasing or other development leading to production of oil and gas from the range shall be undertaken until authorized by an Act of Congress."*

In 2017 congress put forward P.L. 115-97 which in Title II established an oil and gas development program for the Arctic Coastal Plain in Area 1002 to be administered by the BLM *(P.L. 115-97: Individual Tax Reform and Alternative Minimum Tax).* P.L. 115-97 opened up some adjacent Alaska Native Corporation lands as well. On December 20th 2017, President Trump signed it into law *(Comay et al., 2018).* The requirements of P.L. 115-97 are that within a period of ten years from the passing of the law, a minimum of two leases of at least 400,000 acres each, be issued for commercial development. This development however, is restricted by a maximum surface development area of 2,000 acres which may be covered with industrial facilities *(P.L. 115-97 – Title II).*

> *"(i) ACREAGES.—The Secretary shall offer for lease under the oil and gas program under this section—*
>
> > *(I) not fewer than 400,000 acres area-wide in each lease sale; and*
> >
> > *(II) those areas that have the highest potential for the discovery of hydrocarbons."*

and,

> *"(3) SURFACE DEVELOPMENT.—In administering this section, the Secretary shall authorize up to 2,000 surface acres of Federal land on the Coastal Plain to be covered by production and support facilities (including airstrips and any area covered by gravel berms or piers for support of pipelines) during the term of the leases under the oil and gas program under this section."*

When the leases are opened up within the 1002 area, substantial new infrastructure will be required for development. A major component of this infrastructure will be the construction of gravel pads and roads as well as pipeline to connect the 1002 developments to TAPS *(Comay et al., 2018).*

All of the new infrastructure within the 1002 area will likely be built on gravel pads just as has been historically done within State lands.

At the same time as new gravel pads and infrastructure are being developed within the 1002 leases, oil companies will simultaneously be either considering undergoing or actively undergoing DR&R of their existing oil infrastructure facilities within the central State managed lands. Because of the opening up of the 1002 area of ANWR and the decreasing profitability of current oil developments on State lands, consideration is being made of relocating operations to new areas and commencing DR&R of existing operations. Experimental DR&R operations have already been conducted at many sites, however with the exception of large gravel mines, most of them are small areas under an acre of land *(Oil and Gas Technical Report, 2014).* In the coming years after the 1002 area leases are issued it will move from a discussion item to an active task. One of the major challenges of DR&R will be the decision on that removal of any portion of the gravel. Gravel removal must be done in a manner that does not substantially harm the native tundra.

2.5 Gravel Pad Locations and Distribution

To date as of 2018, according to data provided by the Alaska Department of Natural Resources there are 37 operating units in both state and federally managed lands however only 20 units are currently active *(Alaska Department of Natural Resources, 2018).* Not all of the active units however are currently producing oil. Some contain only operations facilities but no production facilities. Appendix A summarizes the data from the ADNR of the operating units and their status. Figure 2 shows the geographic locations of the operating units as well as the surface coverage of gravel on the Arctic Coastal Plain.

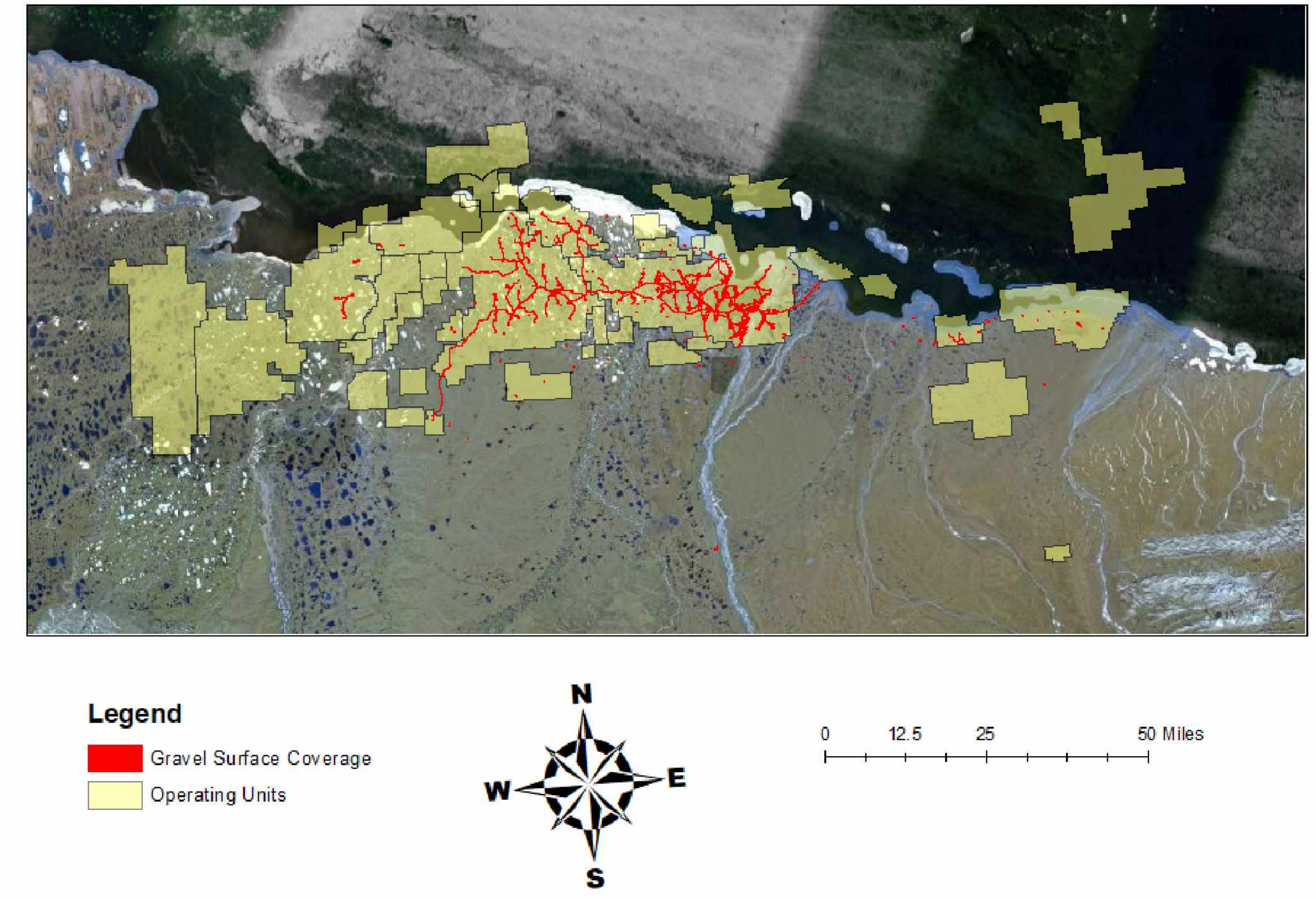

Figure 2: Operating Units and Surface Gravel Coverage – Data Source: ADNR, 2018

Within the 20 active Operating Units according AOGCC data, there are 42 individual industrial facilities *(Alaska Oil and Gas Conservation Comission, 2018).* The facilities are not composed of a single pad but rather contain multiple gravel pads within them connected by a network of gravel roads. As of 2011, across the Arctic Coastal Plain there were 127 production pads, 25 facility pads and 145 support pads *(Raynolds et al., 2014).* These gravel pads are highly variable in size from the smallest, less than an acre, to the largest covering several hundred acres. Most of the gravel pads and roads are relatively shallow, having roughly 2 meters of depth *(Raynolds et al., 2014).* From data provided by the ADNR *(Alaska Department of Natural Resources, 2018)*, the total surface area coverage of gravel pad structures on the Arctic Coastal Plain is estimated to exceed 11,000 acres. From the estimated surface coverage from the ADNR data and an assumed gravel depth of 2 meters, approximately 92 million cubic meters of gravel has been placed down across the Arctic Coastal Plain since the first development in 1968.

2.6 Progression of Design

In the early days of Arctic industrial development very little was known or understood about permafrost or the sensitive nature of arctic tundra. As Alaska began to become more developed, the awareness grew of the need for arctic engineering methods and techniques to prevent problems associated with thawing permafrost and frost heaving ground. However, like all technology, arctic engineering techniques took time to develop and longer to become common practice. As a result, much of the early development in northern Alaska was done in rudimentary ways that damaged and destroyed the sensitive arctic tundra *(Walker & Walker, 1991).*

The early exploration through the 40s and 50s as part of the PET-4 program was done by simply carving a path into the tundra *(Walker & Walker, 1991).* This activity resulted in severe permafrost degradation and damage to the arctic environment. The resulting rutting that occurred created pits up to 5 m which would flood and change the hydrology of the surrounding area *(Orians et al., 2003).* Figure 3 below shows surface scarring near Point Thomson due to geotechnical seismic survey activities. Such surface scarring impacts are typical of industrial activities on unprotected tundra in ice rich permafrost environments.

Figure 3: Aerial Photography of Seismic Survey Surface Scarring Near Point Thomson - Source: Fairbanks Fodar, 2018 - Used With Permission

In the 1960s the technique changed to scraping the surface soils into a raised driveable surface *(Orians et al., 2003)*. This technique also resulted in permafrost degradation creating huge ruts along the sides of the mounded material. This rutting can be seen in figure 4, which is a current satellite image of the tundra surface just west of the Prudhoe Bay BP operated Crude Oil Topping Unit (COTU) facility examined in this study *(Imagery Data source: GeoNorth Information Systems – WMS, http://gis.dnr.alaska.gov/terrapixel/cubeserv/OIM_BDL?).*

Figure 4: Tundra Surface Scarring

Non-frost Susceptible (NFS) material is coarse grained aggregate which has low water retention capacity (specific storage) and minimal ability to move water by capillary forces, thereby eliminating frost heave. Gravel pads built with NFS also provide an insulating layer that keeps permafrost from thawing underneath industrial developments compromising the structural integrity.

By 1968 at the time of the construction of the first oil facility, the use of NFS material had been newly adopted as a construction practice in the Arctic for industrial sites. The native silts of Prudhoe Bay and the Arctic Coastal Plain were recognized as ice rich soils and not suitable for direct construction. Therefore NFS was used at the first oil development in Prudhoe Bay and it has continued to be used in virtually all subsequent developments.

By the 1970s a more complete understanding of the damage of early exploration methods and the need for the use of NFS material was gained *(Orians et al., 2003)*. Unfortunately, the Arctic tundra is very slow to be recover when it is disrupted and much of the damage from the early days of exploration is still apparent on the Arctic Coastal Plain.

The gravel for the pads has been drawn primarily from material sites locally on the Coastal Plain. However, because most of the native soils are permafrost alluvial silts and not construction grade material, the sources for usable NFS gravel are limited. Prior to 1977, the most common source of gravel was floodplain scraping *(Orians et al., 2003)*. In the 1980s the Fish and Wildlife Service conducted a study examining the hydrological impacts of floodplain scraping to the Arctic. Since then, material sourcing has primarily come from gravel mining from 24 open-pit gravel mines in the Coastal Plain uplands *(Orians et al., 2003)*.

2.7 Crude Oil Topping Unit (COTU)

As DR&R operations become a more significant activity, the need for better understanding of the potential impacts to the arctic environment grows larger. A deeper understanding can be gained through both field study and computer modeling of the gravel pad facilities. The 1968 ARCO facility provides such an opportunity. The operation of the facility was taken over by British Petroleum when BP bought out ARCO in 2000. The Crude Oil Topping Unit (COTU) pad has been hydrologically monitored since 1986 when a fuel spill in the pad was discovered. This study uses field measurements from the COTU to develop a computer simulated groundwater model of the pore-water movement through the pad.

Chapter 3 Methodology

The methodology for the modeling in this study was to use the United States Geological Survey (USGS) groundwater flow model, MODFLOW-2005 *(Harbaugh, 2005)* to conduct the groundwater modeling. Mathematically it employs the backwards finite difference numerical method to calculate head values in each of the model cells in a three dimensional finite difference grid and develop a simulated groundwater table and flow parameters over a specified modeled time period. MODFLOW-2005 also employs modular code packages that add additional functionality to the modeling software as needed by the user.

Visual MODFLOW Flex 5.1 is a graphical user interface developed by Waterloo Hydrogeologic, which was used to run MODFLOW for this project *(Waterloo Hydrogologic, 2005).* Visual MODFLOW Flex 5.1 uses both conceptual modeling in which model elements are imported from external data sources into the software, and numerical modeling in which model components are integrated into meaningful elements within the finite difference grid so that the numerical solver can reach a solution.

To apply to the model, data was obtained from the previous Barnes, (2014) study. The Barnes (2014) study was conducted as part of a corrective measures study on the BP operated Crude Oil Topping Unit (COTU) pad related to a fuel spill that was first identified in 1986 and which has been monitored ever since. The groundwater model was developed to cover the period of July 15th through September 13th, 2013 corresponding to the period for which monitoring well data was available *(Barnes, 2014).*

3.1 Study Site Description

The study site for this project is the COTU pad which is leased to British Petroleum at Prudhoe Bay Alaska. The study site is located roughly 7 kilometers just north and slightly east of Deadhorse (Figure 5). It is in the eastern portion of the Prudhoe Bay operating unit. The COTU site is located west of the Sagavanirktok (Sag) River. Figure 5 shows the study site and the surrounding watershed areas.

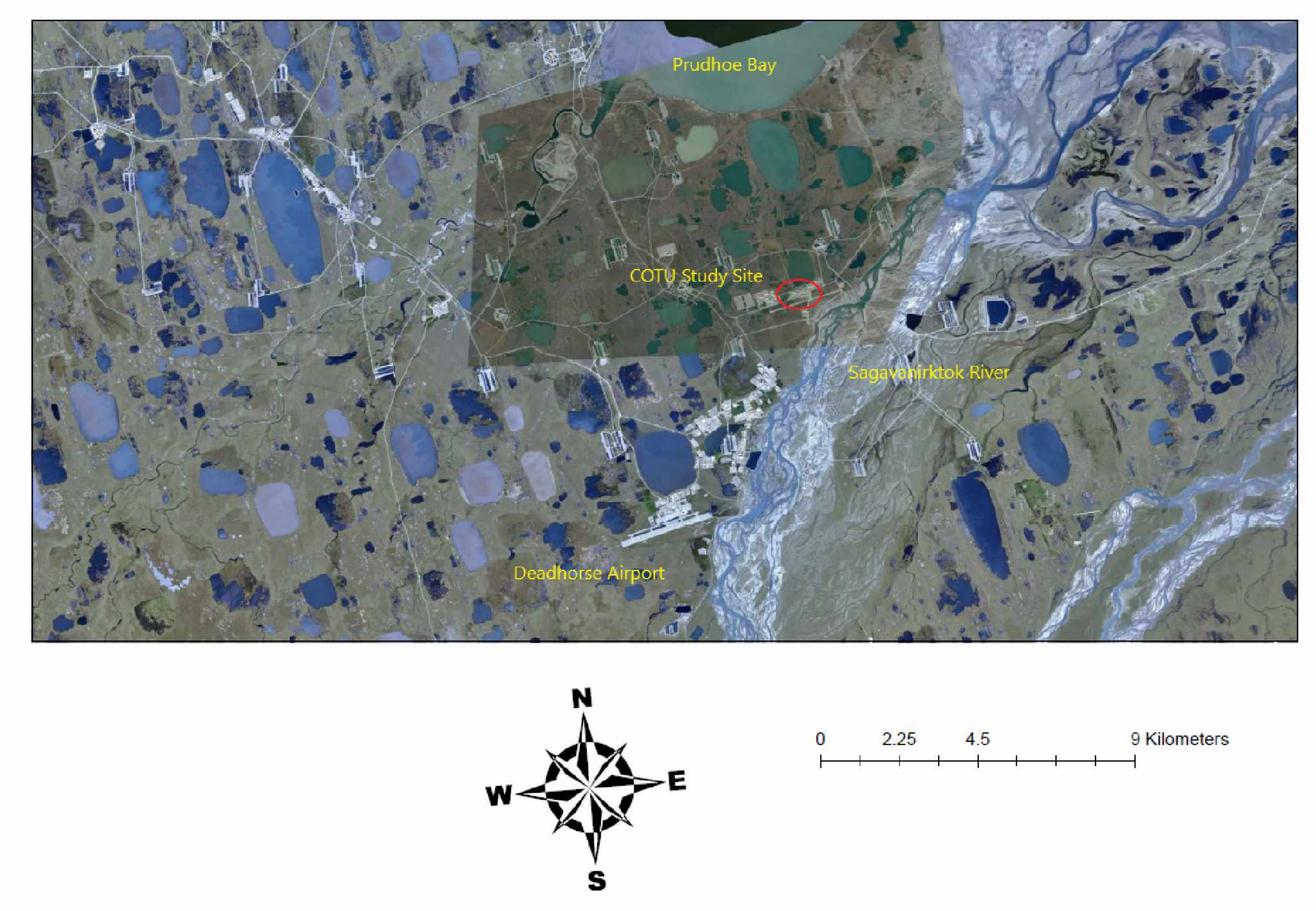

Figure 5: COTU Study Site and Surrounding Watershed Areas

Figure 6 shows the development of the COTU pad over time. The image on the left is an aerial photograph from 1968 when the pad was originally constructed *(Barnes, 2014)*. Note in the image the tundra surface scarring from vehicles driving out onto the unprotected native soils. The image on the right is satellite imagery of the present existing pad infrastructure.

Figure 6: COTU Study Site Development – Source: Barnes (2014)

This study focuses primarily on the COTU southern portion of the pad which is where the available data from the Barnes (2014) study is concentrated. Figure 7 shows a fieldwork photo from the Barnes (2014) study. The image shows the flat topography of the pad as well as standing water collecting along the pad's southwestern edge.

Figure 7: 2013 Fieldwork Photo – Source: Barnes (2014)

3.2 Study Site Watershed Hydrology

Surface water from precipitation and snow melt on the Coastal Plain tends to collect in small ponds and lakes on top of the tundra surface. Stuefer et al. (2017) cited the mean annual Arctic Coastal precipitation near the ocean to be 140 mm/year. Silt that exists in the majority of the subsurface along the Coastal Plain has a relatively low hydraulic conductivity. The active layer typically extends just 1 – 2 meters below the surface of the ground. On the surface the active layer is composed of predominantly organic material and vegetation. Below the active layer the permafrost begins which is composed primarily of fine mineral silts which restricts drainage. Because of the shallow hydraulic gradient, both surface and subsurface water movement is relatively minimal throughout most of the year resulting in large wetlands forming on the Coastal Plain. The surface hydrology in Arctic Coastal watersheds is largely controlled by a single short period of significant water movement in the spring during the annual snow melt *(Suefer et al., 2017)*. During the spring snow melt, the watershed typically experiences a short rapid influx of water into the system. In the hydrologic model, the snow melt runoff takes place early on in the summer in June prior to the beginning of the modeled time period. The impact of snow melt is taken into account in the model through the initial water level conditions.

The COTU pad falls within the Sagavirktok River Watershed. Surface runoff is predominantly influenced by the presence of the river, which is the primary hydrological feature of the watershed. Although the river plays a significant role in the surface hydrology of the watershed, the land has a low hydraulic gradient and like the rest of the Arctic Coastal Plain is underlain by continuous permafrost. As a result, just a short distance away from the river, water movement diminishes significantly. Although the COTU facility is located on the west bank of the Sagavanirktok river, the hydrology of the pad is not believed to be influenced by the river due to both the high elevation difference between the pad and the river as well as the presence of continuous permafrost. From Arctic Digital Elevation Model data *(UMN Arctic DEM, Porter et. al., 2019 – https://www.pgc.umn.edu/data/arcticdem/)* the surface of the river is at 1 – 2 meters above sea level as compared to the 9 – 11 meter elevation of the COTU pad. The topography off the COTU pad drops off very quickly and the water levels in the river are believed to be too low to have a strong influence on the pad hydrology.

3.3 Data

Table 1 below summarizes the data collected for this project and the respective data sources.

Table 1: Data Sets Summary

Data Set	Data Source	Data Reference
Water Levels	Pressure Transducers	Barnes, 2014
Subsurface Geology	Drilling Logs	Barnes, 2014
Precipitation and Climate Data	Deadhorse Airport Weather Station	National Climate Data Center
Surface Elevations	DigitalGlobe Inc. Satellite Imagery	Univ. of Minnesota Polar Geospatial Center
Legal Geographic Data	Legal Documentation	Alaska Department of Natural Resources
Surface Gravel Coverage	Unknown	Alaska Department of Natural Resources

3.3.1 Water Levels

As part of the investigation throughout the COTU facility conducted by Barnes (2014) the groundwater elevation was monitored in a series of wells over the duration of the summer of 2013. Barnes (2014) used pressure transducers installed in 28 wells spread across the COTU South area (Figure 8). Water levels from the pressure transducers in the monitoring wells for summer 2013 were obtained both to inform the development of the boundary conditions and to calibrate the model. These pressure transducers recorded data measurements of water levels on an hourly basis from the time when they were installed on July 11th – 15th until September 13th when they were removed before the winter freeze up. On July 16th, pressure transducers were also installed in three surface water well points: OS-8, OS-18, and SW-8. These off-pad well points provided data about the water levels just beyond the edges of the pad.

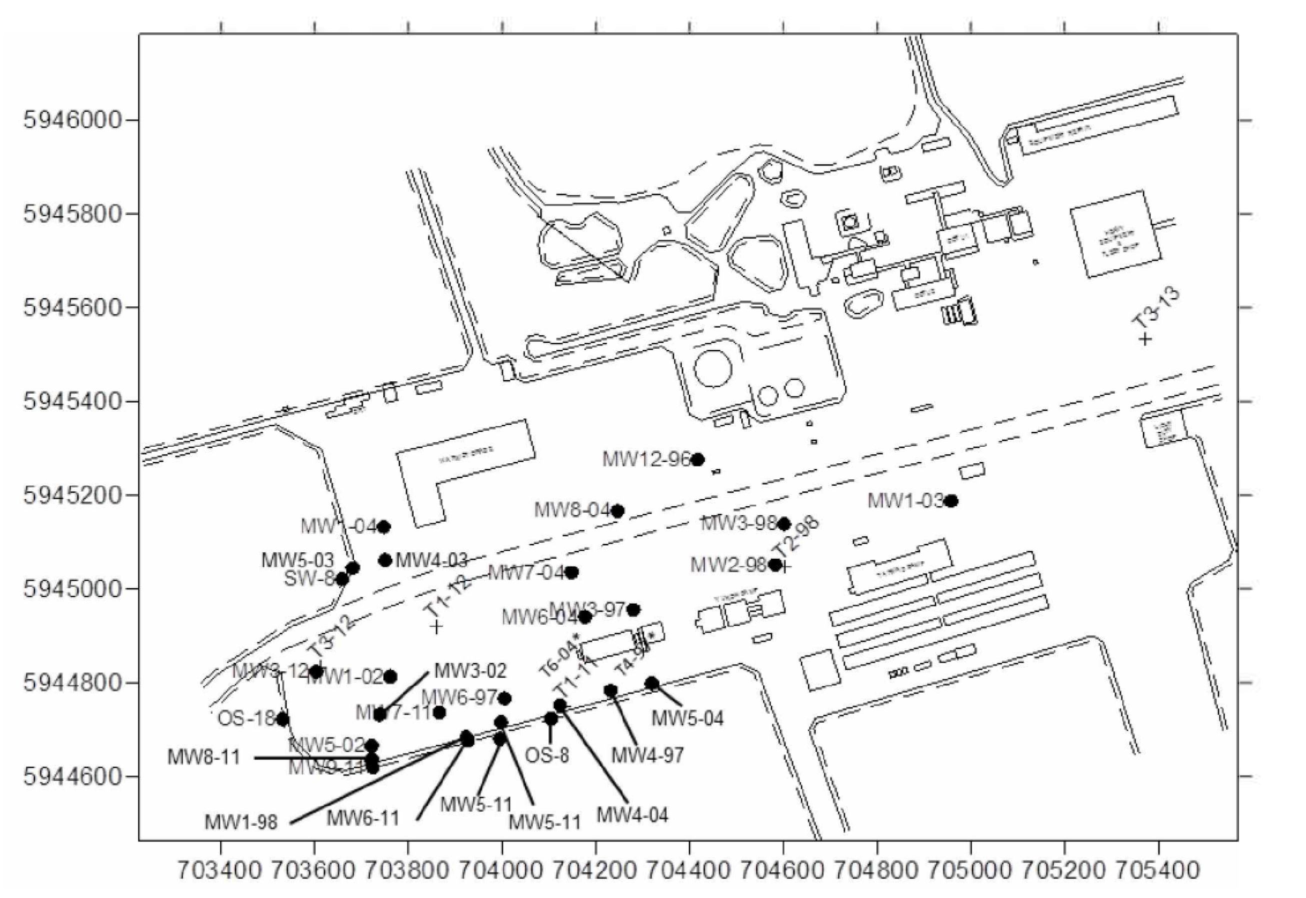

Figure 8: Locations of monitoring wells and thermister strings in 2013 Study

3.3.2 Subsurface Geology

Subsurface soil data of the geology of the COTU structure and the soil below it was gathered for this project from drilling logs. On the drilling logs, the drillers recorded the soil types they were boring and the approximate depths at which transitions occurred from one soil type to another. The depths of soil transitions are not exact scientific measurements because they do not come from geotechincal coreings. Rather, they come from the drillers subjective observations of changes in drill resistance. Although they are not considered scientific quality readings, they do however provide a reasonable approximation of subsurface soil conditions around the locations of the wells. Like the rest of the well data, the drill logs are concentrated in the south western portion of the pad. Most of the wells were drilled prior to the 2013 study some of which were installed as far back as the late 1980s.

In general the ground soil conditions are believed to be unchanged over the course of the time in which the wells were installed from the late 1980s to the present. The possible exception to this however is the frozen soil layer below the tundra which may be spatially variant over time. However, since no data is available on soil conditions and permafrost depths before the well installations, no conclusions may be drawn. The boring log data was used in the model with the understanding that the true representativeness of the frozen soil layer to actual site conditions is unknown.

3.3.3 Precipitation and Climate

Precipitation and climate data for this project was retrieved from the National Climate Data Center database *(NCDC, 2018)*. The data set retrieved from the NCDC was for the Deadhorse airport for 2012 – 2014 although only the summer period for 2013 was required for the model. Because of its close proximity to the COTU pad it is reasonably representative of local precipitation at the study site. The Deadhorse airport rain gauge is a 12 inch Frise automated heated tipping bucket (NOAA, 2019 - https://www.ncdc.noaa.gov/cdo-web/datasets/NORMAL_ANN/stations/GHCND:USW00027406/detail). It is shielded with a standard Alter shield. The precipitation during the modeled period is shown in Figure 9. The data shows that the precipitation comes in short intense rain events, with periods of light precipitation in between and increasing towards the fall season.

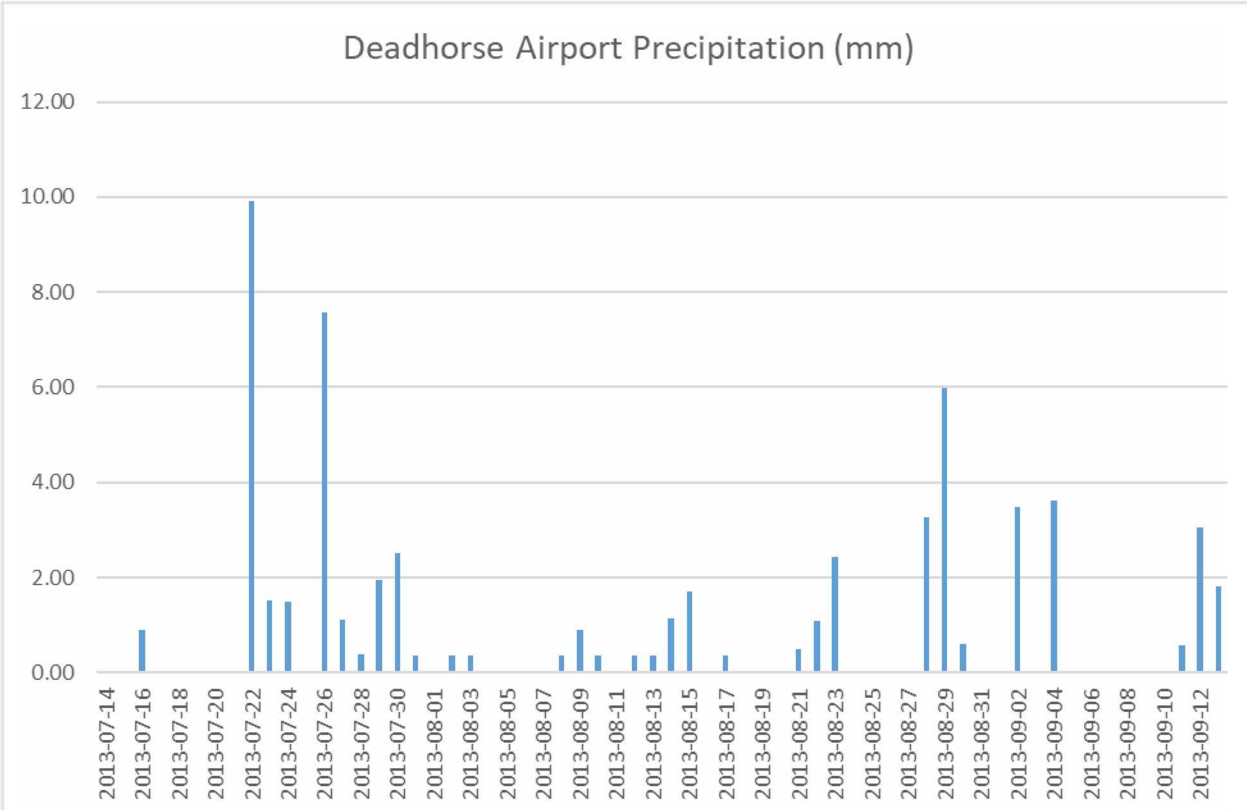

Figure 9: Modeled Period Precipitation

The precipitation data was bias adjusted to account for errors in precipitation measurement following the procedure of Daqing and Goodison *(Daqing & Goodison, 1997).* Biases for consideration were wind, wetting loss, evaporation and trace precipitation. Evaporation was considered to be low enough to be negligible and trace measurements were not recorded in the data set retrieved. Therefore, adjustments were only made for wetting loss and wind. The most significant bias adjustment applied to the data was for wind. Between wind and wetting losses, wind was the much more significant of the two. It should be noted that wind bias was still significant even though the rain gauge was wind shielded. A wind shield will reduce but cannot eliminate the effect that wind bias may have on precipitation data. After the data adjustment, the precipitation values during the modeled months of 2013 were 10 % higher in July, 13 % higher in August, and 22 % higher in September. The increasing adjustment can be attributed to windier conditions later in the season.

3.3.4 Surface Elevations

Surface elevations at the site were obtained from the Arctic DEM database hosted by the University of Minnesota's Polar Geospatial Center. *(UMN Arctic DEM, Porter et. al., 2019 – https://www.pgc.umn.edu/data/arcticdem/)* Surface elevation data was used to inform specific decisions about model elements such as the boundary condition head values. It was also used to help develop model assumptions about surface water elevations, movement and flow patterns in areas just outside the model itself. The elevation data used to construct the digital elevation models was originally generated from the DigitalGlobe Inc. Satellite Constellation *(UMN Arctic DEM, Porter et. al., 2019).* The data is accurate at the 0.5 m level *(UMN Arctic DEM, Porter et. al., 2019).*

3.3.5 Legal and Geographic Data

Legal and geographic data were provided by the ADNR, as well as obtained from the AOGCC although they were not used for modeling directly. These data were useful for helping understand the background of oil developments on the Arctic Coastal Plain and their legal distribution within State lands. The geographic and legal data was useful for providing background information on oil operations at present. No data was obtained for Federally managed lands in either the NPRA or the 1002 area however at present, very little oil infrastructure has yet been constructed in either of these areas so in depth investigation was not necessary. The legal geographic data is believed to have been developed from ADNR legal leasing documentation. The spatial resolution of the legal data is not known as that information was not included in the metadata associated with it.

3.3.6 Surface Gravel Coverage

The ADNR also provided spatial GIS data for the surface coverage of gravel on the Coastal Plain including both roads and pads. This data was used to estimate the total area and volume of gravel surface coverage across the Coastal Plain. For this data set, no metadata was provided. Therefore, both the method of the data development and the spatial resolution of the data set are not known.

3.4 Modeling Process Overview

Once the data was obtained, it was processed primarily in ArcGIS *(ESRI, 2019)* and then imported from there into the Visual MODFLOW Flex 5.1 user interface. Visual MODFLOW Flex 5.1 is structured around a two stage process of model development. The first stage of modeling is conceptual modeling and the second stage is numerical modeling. In the conceptual modeling stage, geospatial data objects are constructed externally and then imported into Visual Flex to develop the model structure. During this stage, the model structure and property zones are defined representing local soil geological conditions. In the numerical modeling stage, the conceptual model is converted into a three dimensional finite difference grid model with property values assigned to the model cells from the conceptual model elements. It is in the numerical modeling stage that the model is computationally solved using the USGS MODFLOW-2005 *(Harbaugh, 2005)* engine and a hydrologic water table generated. In the numerical modeling stage more specific adjustments to the model are made by modifying the model on a cell by cell basis. Individual modifications can be made to the model parameters including both cell properties and boundary conditions. Changes can be made to individual cells or to groups of cells. In addition, observation wells are defined for the model in this step which are then used to calibrate the model against once it has been run.

3.5 Conceptual Modeling Property Zones

The conceptual modeling stage begins by defining some initial modeling parameters such as model units and the start date of the model. After the initial setup, the external data objects are collected by importing them into Visual Flex. Once the data objects have been collected comes the first major step of model development, constructing the conceptual model structure. The conceptual model structure is defined by property zones which are three dimensional regions of space for which specific modeling properties are assigned such as hydraulic conductivity, storage, and initial heads. During the conversion to numerical model step, the grid cells are assigned property values according to which spatial property zone they fall into. For this model, three property zones were defined: gravel, silt, and permafrost. Table 2 below summarizes the significant property values assigned in each of the three zones.

Table 2: Property Zones

Property Zone	Hydraulic Conductivity K (m/s)	Storage Specific Yield S_y
Gravel	0.01	0.35
Silt	1.0×10^{-6}	0.1
Permafrost	1.0×10^{-12}	0.05

The initial heads were assigned from a topographical surface developed in ArcGIS *(ESRI, 2019)* from the observed water level values in the monitoring wells on the first day of the modeled period (July 15, 2013). The spatial distribution of the monitoring wells did not uniformly cover the modeled area. Because the spatial distribution was non-uniform, the initial heads surface is considered to be more spatially accurate in areas of higher well density. In areas of low well density, particularly the northeastern end of the model, the accuracy of the initial heads surface is not believed to be as high. The area of highest accuracy is believed to be along the southwestern edge of the model where the largest number of wells were concentrated.

The natural neighbor spatial interpolation method used to generate the surface is only able to generate values for raster cells which are geometrically contained completely within the area where the monitored wells are located as shown in figure 10 below. Because not all of the wells in the pad were monitored, portions of the model that fell outside of this area did not get initial head values assigned to them from the topographical water table surface. Instead in the model these areas were assigned values manually that were close (+/- 0.3 m) to the values on the edges of the interpolated surface near where they were being applied. The exception to this was the southeast portion of the pad in which higher initial heads (+/- 1.5 m) were applied. Although there is a known discrepancy between the observed southeastern edge heads and the heads applied, the higher initial heads in this portion were necessary in order for the numerical solver to converge along the southeast boundary of the model during the early time steps. The initial water table surface also did not include the water level measurements for the three surface water wells OS-8, OS-18 and SW-8 because they fell outside the gravel pad structure. The initial heads surface was developed only using the monitoring wells which were in the pad itself. Figure 10 shows the portion of the modeled area for which interpolated initial head values were applied.

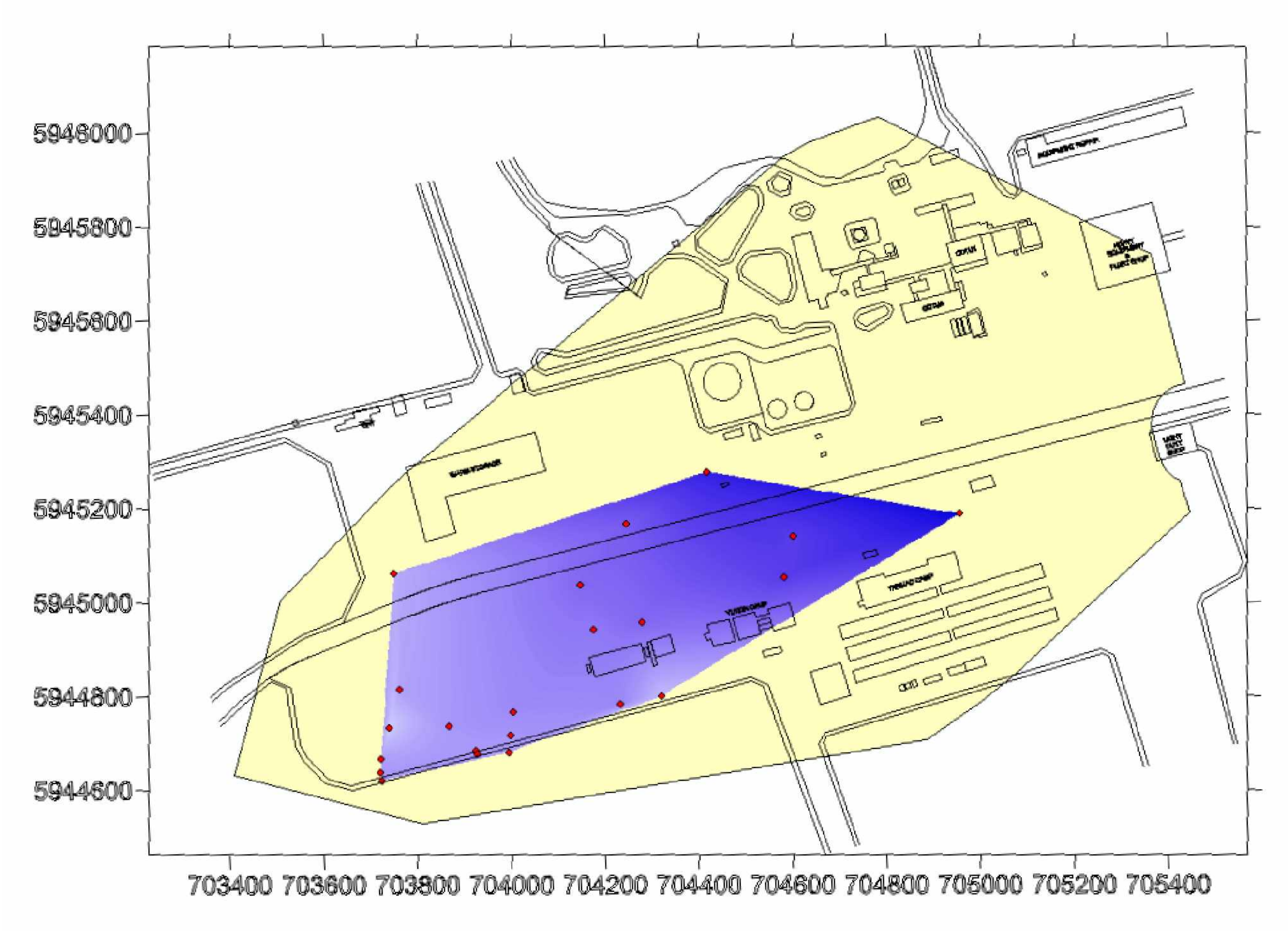

Figure 10: Area of Initial Heads Within Modeled Domain

The property zones for the model were defined by the area in between structural horizons developed from imported surfaces from ArcGIS. Figure 11 below shows the interpolated GIS surfaces displayed in ESRI ArcScene *(ESRI, 2019)*. The surfaces have been exaggerated 35 times vertically to better visualize the topographical relief. The gray surface represents the gravel layer, the brown is the underlying silt and native tundra, and the blue is the frozen soil layer. The yellow layer on the bottom is a horizontal base plane set at an elevation of 6 m (above mean sea level).

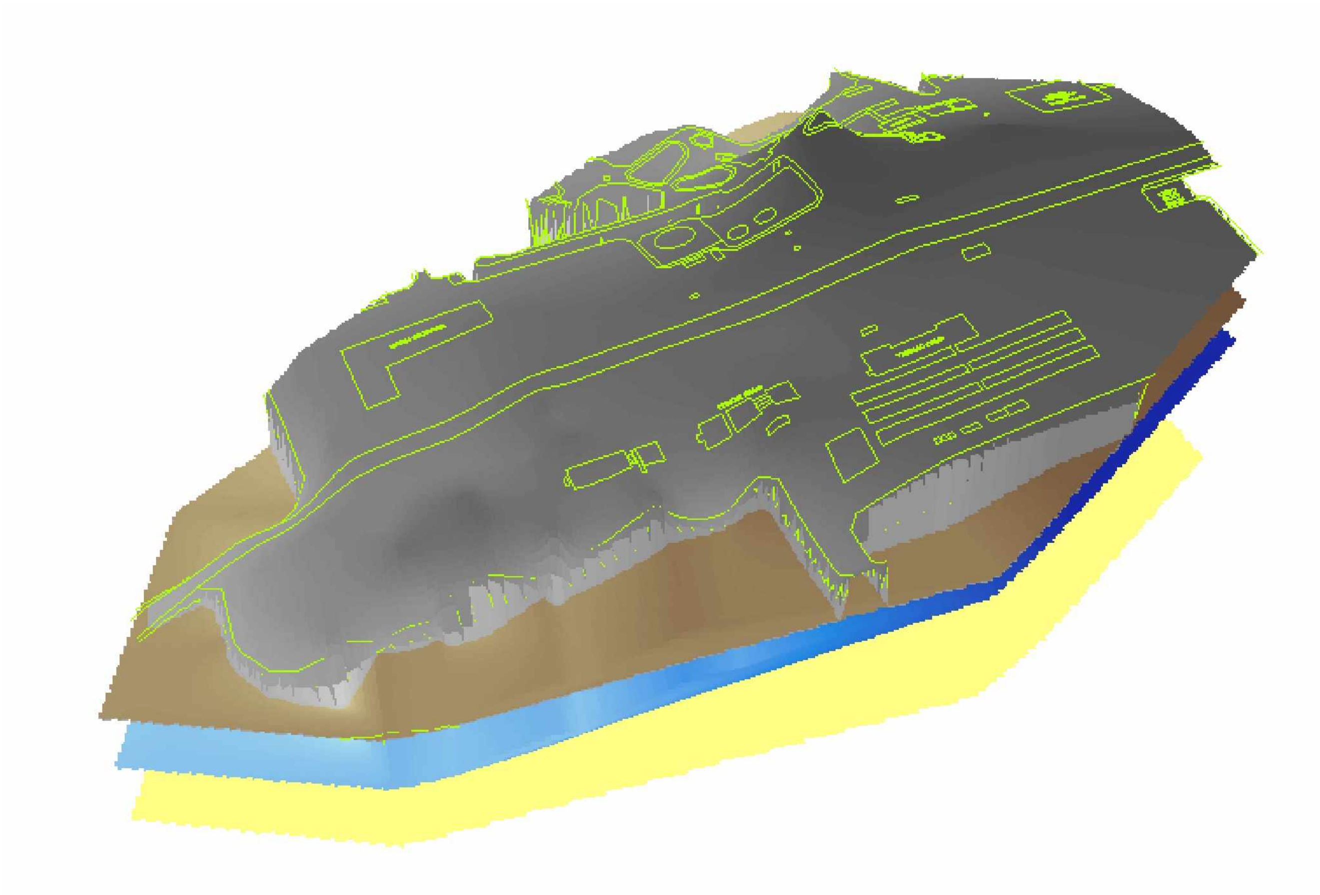

Figure 11: Model of Surfaces Displayed in ESRI Arc Scene – Vertically Exaggerated 35 Times

In ArcGIS, the surfaces were constructed using the natural neighbor spatial interpolation method from known elevations reported in driller boring logs during well installation. The natural neighbor method was chosen for this purpose primarily due to the honoring of the data points preserving their elevations in the surfaces its creates. Honoring the data points in the method of spatial interpolation was important for the surfaces since the data points used were known elevations from the boring logs. One of the major limitations in constructing the data surfaces was data density. Some portions of the surfaces particularly in the north eastern portion of the pad suffer from lack of sufficient data density. As a result, the accuracy of the topographical surfaces in these areas in comparison to actual site conditions is questionable. In addition, in these areas, the relief of the surfaces is much lower as well. However in the south western portion of the pad where there is good data density, there is much higher surface relief and better confidence in surface accuracy.

The drilling logs used to construct the surface, represent wells from a number of different years and times of the year when the wells were drilled. Most of the wells used in the Barnes (2014) study were already in place on the pad from prior studies. The data from the drilling logs therefore comes from a number of different years rather than from the year (2013) specific to the this project. In addition, most likely the wells were not drilled precisely at the period of the year of maximum depth of thaw, or even at the same time of year between wells. Because of all of these factors, the permafrost layer should be considered a best guess scientific approximation of frozen soil elevations. The actual site conditions may be significantly spatially variant from the permafrost layer used in the model.

When constructing the gravel surface, some regions of the surface were in areas of the model where no gravel had been placed and native tundra was exposed. In these areas the surface elevation for the gravel layer was set to be equal to the elevation of the interpolated tundra surface because Visual Flex requires the surfaces be defined within the entire domain of the modeled area. When developing the finite difference grid, cells in these areas were set to inactive.

The interpolated tundra surface was constructed with the objective of following as closely as possible the contours of the original surface topography prior to the pad construction. Figure 12 shows the topolines of the interpolated silt layer overlain on the aerial imagery of the pad area from 1968. It can be observed, that the interpolated surface reflects relatively well the original surface topography in the image by examining the topographic features in the image such as the tundra ponds which line up closely with each other.

Figure 12: Aerial photograph of the location of the COTU in 1968 with the boundaries of the COTU south pad overlaid and the topography contours of the interpolated tundra surface. Source: Barnes (2014)

Another significant data limitation was the frozen soil surface. For this model, the depth to frozen soil was assumed to be spatially and temporally static over the entire duration of the modeled period although in the real world, thaw depth is spatially and temporally dynamic over the course of the season. Although the thaw surface is technically dynamic, the seasonal depth of thaw typically reaches approximately 80% of its maximum value by the end of July and grows slowly thereafter. Therefore, since the modeled period does not begin until mid July, the static frozen soil surface was believed to be reasonable for application in in the model. A static thaw depth for this model was employed for several reasons. The first reason was a lack of data. The geologic boring logs from the wells used to construct the surfaces represented single occurrences of thaw depths rather than temporal trends. The second reason was that MODFLOW-2005 *(Harbaugh, 2005)* does not support temporally variable grids without additional packages and coding. Therefore, a static depth of thaw was used.

For the purposes of model development, it was assumed that the thaw depth was at its maximum for each of the frozen soil elevations in the drilling logs. The drilling logs were variable in what period of the year they were recorded in. Therefore, although they are most likely not necessarily representative of maximum thaw depths, no other data set was available. The true maximum thaw depths are likely to be lower than the interpolated surface but cannot be higher since the depths recorded in the drilling logs cannot exceed the maximum thaw.

3.6 Defining the Grid

Once the property zones for the model were complete, the finite difference grid could be established. For the model, a finite difference grid composed of 5 m x 5 m cells was used. The grid was developed using the three layers following the topography of the structural horizons from the surfaces developed in GIS. The third (bottom) layer of cells which exist in the permafrost were set to inactive to create a no flow boundary condition on the base of the model. Setting the cells on the bottom as inactive, thereby making them a no flow boundary was assumed to be reasonable since the permafrost is considered an impermeable surface. Some portions of the model domain included areas of silt surface exposure where no gravel was present. In these areas, the finite difference cells were set to inactive such that the finite difference grid for the model only included cells either in or directly below the gravel pad itself. Cells in the model domain which fell beyond the edges of the gravel pad were excluded by being turned inactive. In addition, cells in the northeastern portion of the pad were turned inactive as well bisecting the pad. This was done to restrict the model to only the areas for which data was available. Data from the Barnes (2014) study was not considered sufficient to model in the northeast portion of the pad because there was an insufficient number of wells installed to get good data in that region. Figure 13 shows the finite difference grid overlaid on top of the property zones for the model.

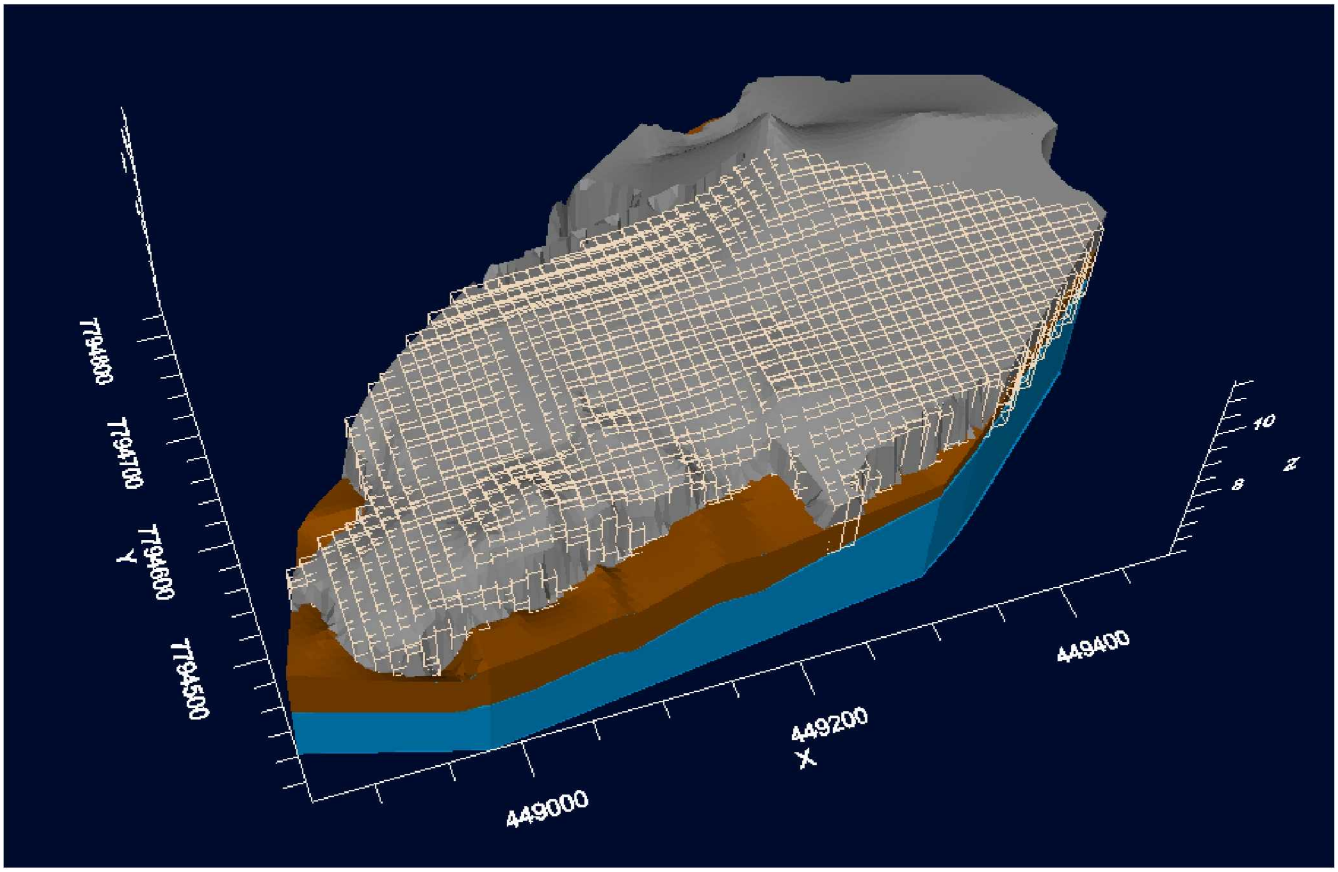

Figure 13: Finite Difference Grid – Exaggerated 35 Times

3.7 Boundary Conditions

To run, the numerical model required boundary conditions to be set up to solve for the water heads using the backwards finite differential method. In the model, along the bottom a no flow boundary was established by inactivating all of the cells beneath the model. This boundary condition was used to simulate the effect of permafrost beneath the model which is considered to be an impermeable soil layer. Around the edges of the model, constant head boundaries and a specified flux boundary were used to simulate the water flowing into and out of the pad at the edges. On the top of the model, a recharge boundary condition was applied to account for infiltration into the pad of precipitation.

3.7.1 Model Edge Boundary Conditions

The cells around the edges of the gravel pad were assigned boundary conditions based on the conditions beyond the edges of the model. Some portions of the model domain extended further out into the tundra beyond the gravel edge. In these areas, the cells beyond the gravel edge were set to inactive and therefore were not included in the finite difference grid. For most of the model edges, constant head boundary conditions were applied, however along the northeastern edge of the model a specified flux boundary condition was used instead because this portion of the model cut through the pad as opposed to following along the gravel edge. Figure 14 shows the delineation of the boundary conditions in the model. The red boundary conditions represent constant heads and the blue boundary condition represents the specified flux.

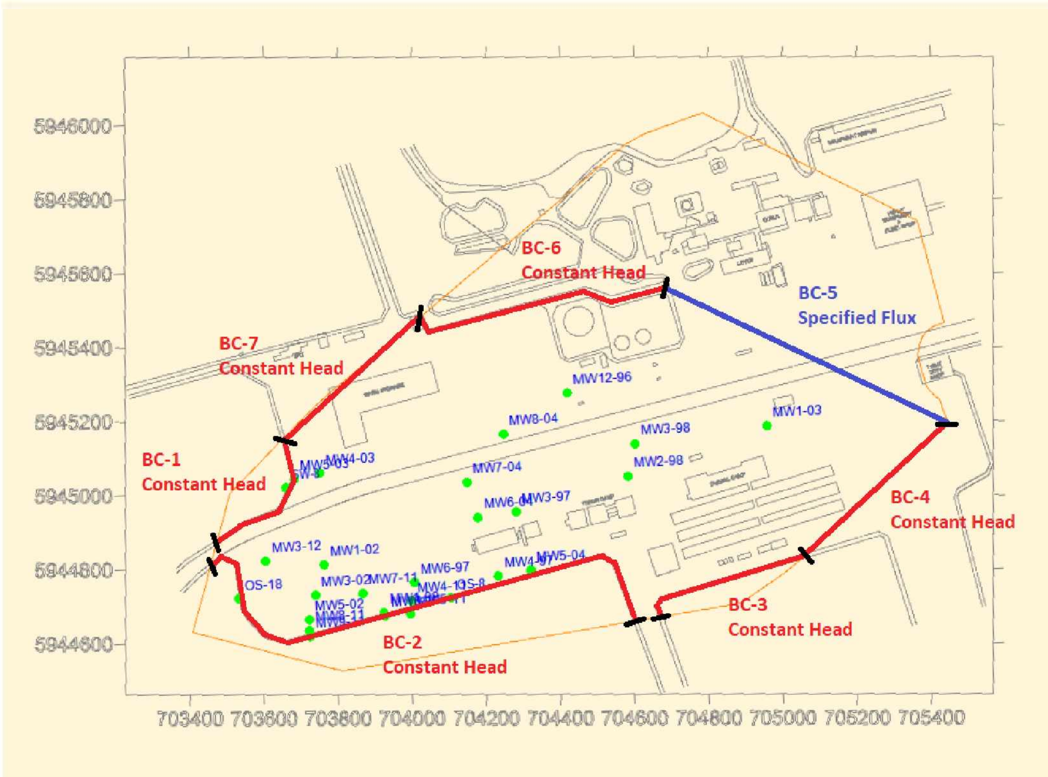

Figure 14: Model Edge Boundary Conditions

The model boundary conditions consisted of 7 individual boundary condition cell groups identified as BC-1 through BC-7. The boundary conditions were all set up as constant heads except for BC-5 which was set up as a specified flux. A constant head boundary could not be reasonably applied along the BC-5 edge since open water conditions do not exist there which are typically where a constant head boundary would be used. The constant head boundary, head values were estimated from the observed surface water monitoring well data from SW-8, OS-18, and SW-8. For use in the groundwater model that was run with stress periods in days, the hourly water level readings were consolidated into daily mean values. Uniform head values for the constant heads on the south side of the model were applied for the entire duration of the modeled period because the variation in the observed open water levels throughout the season was low. Only BC-5, BC-6 and BC-7 were varied throughout the season. Table 3 provides the values used for each of the boundary conditions.

Table 3: Boundary Condition Head Values

BC	Head Value (m amsl)	Head Reference
BC-1	8.6	SW-8
BC-2	9.0	OS-18 / OS-8
BC-3	9.5	OS-18 / OS-8
BC-4	10.0	Model Calibration
BC-5	SPECIFIED FLUX (10 – 25 m/day)*	Model Calibration
BC-6	9.5 – 10.0	Model Calibration
BC-7	9.0 – 9.5	Model Calibration

* The specified flux was input into the model in units of m/day. The flux volumes were determined in the model by multiplying specified flux input length by the individual areas of each cell face through which the flux was specified.

Boundary condition BC-1 was developed from the off-pad water level measurements for the observation well SW-8. For the constant head, the mean value was taken of the observations throughout the season of SW-8, which equaled 8.6 m above mean sea level. This approach was considered reasonable because there is very little variation in the water level throughout the course of the season. The standard deviation for the water level measurements in SW-8 was 0.05 m.

Boundary condition BC-2 was similar to BC-1 based on the open water level measurements. BC-2 took its value from the observation well OS-8. The mean seasonal water level for OS-8 was 9.0 m. OS-8 like SW-8 had very little seasonal variation in its measurements. The standard deviation for the season was 0.02 m. Figure 15 shows the measured water levels in OS-8 over the course of the season. The sharp dip towards the end of the season is believed by Barnes (2014) to be caused by a temporary equipment malfunction. The blue area surrounding the line represents the error in the water level measurement.

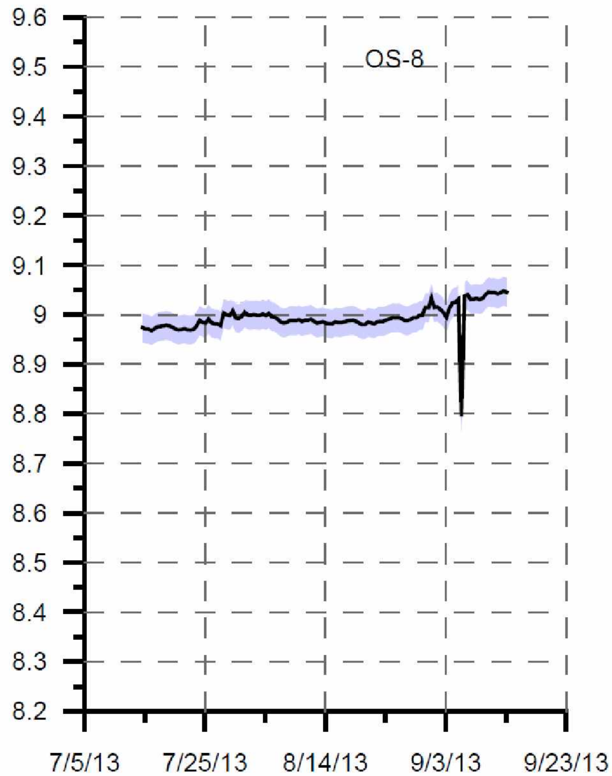

Figure 15: OS-8 Water Levels - Source: Barnes (2014)

The boundary condition BC-3 was also along the edge of the pad adjacent to an open tundra pond. No water level data however was available for the tundra pond. Boundary conditions BC-3 and BC-2 are separated by a gravel road between them. Because the water movement was found in the Barnes (2014) study to be predominantly in the southwest direction the head in the tundra pond adjacent to BC-3 was set to be slightly higher than the head in the pond adjacent to BC-2. BC-3 was assigned a head value of 9.5 m.

Boundary condition BC-4 was set up as a constant head boundary although technically it does not follow the edge of the gravel pad directly. The model domain towards the eastern side did not extend all the way to the gravel edge because of low data availability. The boundary condition BC-4 therefore followed the edge of the model domain rather than the edge of the gravel pad. A constant head however was still chosen to be applied to BC-4 because although technically it cuts through the pad, the edge of the gravel was roughly no more than 25 – 50 meters away from the edge of the model domain which is a relatively short hydrologic distance. Therefore it was determined reasonable to apply the constant head as though it were open water along that edge even though technically it is subsurface head. To account for the difference between the true open water conditions of BC-3 and the adjacent subsurface head conditions of BC-4, the hydraulic head was increased in BC-4 from the 9.5 m head in BC-3. BC-4 was applied a head value of 10.0 m. As a result, there is a 0.5 m head difference that exists at the intersection of the two boundary conditions. This phenomenon can be observed in the final water table which is produced when the model is run.

BC-5 was selected as a specified flux boundary condition as opposed to a constant head like the others. The reason for using the specified flux boundary for BC-5 was that the model edge along that portion runs through the middle of the pad rather than falling along the edge of the gravel. The portion of the pad through which the BC-5 edge cuts continues on for roughly 600 m before reaching the north eastern edge of the pad. The constant head boundary condition is only reasonably applied under conditions where a known constant head source at the edge of the model exists (such as a lake or other water body). Along the edge of the portion of the model which cuts through the middle of the pad no such hydrological feature is present and so therefore the specified flux boundary condition was used instead of the constant head. In the specified flux boundary condition, the flux is defined for each of the boundary cells to determine the head value in the cells. The specified flux boundary condition therefore simulates horizontal recharge entering the model along its length. In the Visual MODFLOW Flex 5.1 user interface, the specified flux boundary condition is assigned by the user as a linear distance value per time. This value is then multiplied by the cross sectional area of the finite difference cell to which it is applied in order to get a volume flow rate into the model. Along the northeastern edge of the model where the specified flux was applied, although the cell widths were constant at 5 m the cell depths were variable. Therefore the cell face area by which the linear flux was multiplied for each cell was variable due to the non uniform cell heights along the model edges between 1 – 2 m. Typical cells along this edge were assumed to be 1.5 m deep giving a typical cross sectional area of approximately 7.5 m^2. Based on this area, the specified flux values applied were 10 – 25 m/day which therefore produced fluxes in any given BC-5 cell between 75 – 188 m^3 / day in each cell increasing over the duration of the model.

The northern boarder of the model was divided up into two final constant head boundary conditions BC-6 and BC-7. BC-6 encompassed the most northern edge of the model and BC-7 covered the portion adjacent to BC-1. In the absence of substantial data along the northern edge of the model it was determined best to apply the two boundary conditions in a stair step manner BC-6 being higher than BC-7 since the gradient moves from a high head in the eastern portion of the model towards a lower head in the western portion of the model. Since the water gradient runs primarily towards the southwest, BC-6 is expected to have a higher head value, particularly in the portion closer to the northeastern end of the model. Due to an absence of data along the northern edge of the model the two northern constant head boundaries unlike BC-1 through BC-4, did not have a single constant head value applied but were gradually increased over time. BC-6 was increased over the duration of the modeled period from 9.5 m – 10 m. BC-7 was increased from 9.0 m – 9.5 m. These values were chosen based on trial and error testing to determine what values produced the best model calibration results.

3.7.2 Precipitation-Recharge Boundary Condition

It is was originally hypothesized that precipitation events are one of the major controlling factors for pore-water movement in the COTU pad. Recharge is applied to the model as a boundary condition of specified flow into the top. It can be applied as either a uniform specified constant value or as corresponding to a time schedule of precipitation data. For the recharge boundary condition in this model, a time schedule was used of precipitation data from the Deadhorse airport weather station. In the model an infiltration rate of 75 % of the precipitation was applied. Because the true infiltration rate of the soil was not known, a 75% value was arbitrarily selected to initially apply for the recharge. After the model had been run it was determined that the recharge inputs into the model were too small to have a significant impact in comparison to the other boundary conditions. Therefore the 75 % value was never adjusted any further.

3.8 Model Temporal Resolution

The capabilities of the model are limited by the resolution of the data used to construct it. Running the model at a temporal resolution finer than the data used to construct the model does not necessarily produce more accurate modeling results. The temporal resolution of the data therefore is considered the ultimate boundary for the finest resolution for the model to be run. The pressure transducer data had a temporal resolution of hourly readings. The precipitation data set only had daily average readings. The COTU model was run for 61 stress periods at a rate of one stress period per day. Each stress period was composed of 10 time steps within it for a total of 610 time steps over the course of the summer (2.4 hours per time step). The total length of the modeled time period was from July 15th 2013 through September 13th 2013. The modeled time period was chosen to correspond to the days for which pressure transducer data was available.

Chapter 4 Results

The results of the groundwater model are useful in helping us more thoroughly understand the COTU site hydrology giving insights that direct observation cannot provide. Through model calibration, the hydraulic properties of the gravel pad structure itself and the boundary conditions controlling the flow of the pad pore-water have been more clearly defined. The hydraulic properties and the boundary conditions of the model were adjusted until model calibration was achieved per the recommended methodology of Anderson et al. (2015). Model calibration was conducted by comparing the water levels calculated in the COTU model to the measured water levels in the wells from the Barnes (2014) study over the modeled period from July 15th 2013 through September 13th 2013. Through model calibration the model properties of hydraulic conductivity and specific storage have been more clearly defined. Although their exact values are not known (and are likely variable) the model has helped determine approximately what they must be to produce the observations seen in the data. The model generated water balance is another useful result from the model, which enables us to understand the total volumes of water movement through the system more completely. Finally, the groundwater model shows the overall water levels in the pad and the contributions to and removals from the system.

4.1 Model Calibration

The model was calibrated by adjusting model hydraulic conductivity, storage and some of the boundary conditions until it was determined that the modeled heads sufficiently closely represented the observed data following the recommended methodology by Anderson et al. (2015). For 8 individual stress periods out of the 61 throughout the modeled period, plots were generated of modeled versus observed head values in the wells. The stress period days for calibration were chosen based on the days of the extremes of the well data, both the highest and the lowest mean water level measurements as well as additional random stress periods. Ideally, in a calibrated model the water levels predicted by the model equal the true observed measured water level values. This ideal condition is rarely achieved. Hence, guidelines that address acceptable deviations from the ideal condition have been developed by Anderson et al. (2015). In the COTU model, the deviation between predicted and observed fall outside these guidelines. Possible reasons for the deviations will be addressed.

4.1.1 Hydraulic Conductivity

Hydraulic conductivity was one of the major parameters that was modified to achieve model calibration. The model was set up with each of the three model layers having its own uniform hydraulic conductivity. Adjustments were made to the conductivity of each layer during model calibration. Table 4 shows the calibrated hydraulic conductivity values for each model layer.

Table 4: Model Hydraulic Conductivities

Property Zone	Hydraulic Conductivity (m/s)
Surface Gravel	0.01
Subsurface Silt	1.0×10^{-6}
Frozen Soil	1.0×10^{-12}

From the model calibration the gravel layer cells were assigned a hydraulic conductivity value of 0.01 m/s. Typical values for gravel materials range from 3.0×10^{-2} m/s to 3.0×10^{-4} m/s *(Schwartz and Zhang, 2003)*. The value used in the model may be somewhat high because typically the gravel pads are very heavily compacted. The value was used however because it is still within the typical range of gravel hydraulic conductivities and results in an adequately calibrated model. The subsurface silt value of 1.0×10^{-6} m/s was selected also based off of model calibration. Typical silt values range from 2.0×10^{-5} m/s to 1.0×10^{-9} m/s *(Schwartz and Zhang, 2003)*. The selected value for silt was on the high end of the silt range, however the silt layer in the model only represents those unfrozen soils above the permafrost and below the gravel. These soils are considered to be predominantly silt but may be mixed with arctic organic matter which may increase the hydraulic conductivity of the soil. Finally, the frozen soil was given a value of 1.0×10^{-12} m/s. The frozen soil is considered to behave similarly to rock in that it does not permit significant water movement. Depending on the geology, rock can have an extremely wide range of conductivities from 2.0×10^{-2} m/s to 3.0×10^{-14} m/s *(Schwartz and Zhang, 2003)*. If there are flow pathways such as fractures through the rock, it will be more conductive. Because the conditions of the frozen soil at the site were not known, a lower hydraulic conductivity of 1.0×10^{-12} was chosen in order to restrict flow on the bottom of the model as much as possible.

4.1.2 Storage

Storage was also used for model calibration. MODFLOW allows for the input of several different storage related parameters including specific storage (S_s), specific yield (S_y), effective porosity (φ_E), and total porosity (φ_T). Specific yield is the storage term typically used for unconfined aquifers. Because there is no confining layer in this model, it was considered to be a completely unconfined aquifer. Therefore, for development and calibration of the model, only specific yield was varied. The final values for S_y of the calibrated model are presented in table 5.

Table 5: Model Storage

Property Zone	Sy
Surface Gravel	0.25
Subsurface Silt	0.08
Frozen Soil	0.01

Depending on the material type, the specific yield can very from 0.01 to up to 0.40 by volume (volume retained over total volume) *(Schwartz and Zhang, 2003).* The specific yield for gravel can range from 0.13 – 0.40. Coarse gravel has a lower specific yield while fine gravel has a higher. The gravel for this project was within this range at 0.25. The silt range for specific yield can vary from 0.01 – 0.39. The silt for used in the model was on the lower end at 0.08. Generally specific yields for silts are lower than specific yields for gravels. For the frozen soil, typical specific storage values were not available. The frozen soil however is believed to be composed predominantly of silts. Since any water content in it is believed to be frozen however, the specific yield is therefore expected to be low. Therefore a lower specific yield value of 0.01 was chosen for the frozen soil layer in the model.

4.1.3 Model Edge Boundary Conditions

Another one of the model elements that was used for calibration was specific model edge boundary conditions. Because in the northern and eastern portions of the model there was insufficient data to construct definitively established boundary conditions, the constant heads along the northern portion of the model and the specific flux along the northeastern edge were used as calibration parameters. The heads in boundary conditions BC-4, BC-5, BC-6 and BC-7 were varied until the model was calibrated. Boundary conditions BC-1, BC-2 and BC-3 were not varied for calibration because their head values were obtained from water level measurements from the Barnes (2014) study.

Boundary conditions BC-1 (8.6 m amsl) and BC-2 (9.0 m amsl) being fixed constant heads, are reasonably believed to be representative of the actual site conditions since their head values came directly from observed water level measurements that only change slightly throughout the course of the season. BC-3 also being on the southern edge of the pad was given a value of 9.5 m. BC-3 was near enough to the water body measured by OS-8 that it was still considered reasonable to use the OS-8 measurements for its head. The head was increased 0.5 m from BC-2 due to the fact that it is slightly upgradient and separated by a gravel road from the main water body. BC-4 being inside the pad rather than on the edge was given a slightly higher head value again (10 m amsl) due to higher pore pressure and the fact that it is further upgradient. Without monitoring well data on the northeastern end of the pad, it is difficult to judge the veracity of the specified flux boundary condition BC-5. What is known however, is that the edge of the model along which the specified flux is applied is the most up-gradient portion of the model which means that a substantial amount of water is believed to be entering the system through northeastern end of the pad. Increasing the flux rates to higher values tended to produce a better model calibration. Therefore, the flux rates of 75 – 188 m^3 / day are believed to be reasonable. The boundary condition BC-6 was varied from 9.5 – 10.0 m and BC-7 was varied from 9.0 – 9.5 m. The BC-7 values were chosen to be somewhat close to the adjacent value of 8.6 of BC-1. BC-6 being just upgradient of BC-7 was given values 0.5 m higher. Like the specified flux boundary, without quality data on the northern side of the pad, the accuracy of these boundary conditions is not known, however the final values chosen produced satisfactory model calibration, therefore they were believed to be reasonable.

4.1.4 Method of Calibration

According to Anderson et al. (2015), there is no common universal modeling standard or guidlines for what is considered acceptable model calibration. Anderson states that model calibration is somewhat subjective to the modeler but poses using one potential method in which the root mean squared error (RMSE) of each calibration plot is compared to the difference between the highest and lowest observed head in the calibration plot. The suggested guideline Anderson et al. (2015) recommends for model calibration is that the value of the RMSE be within 10% of the total observed head difference in each calibration plot.

Due to the variability and unknowns of the boundary conditions in the model the 10 % recommendation could not be reasonably attained for the COTU model. One potential factor causing the challenge of attaining the 10% RMSE goal was the data from the monitoring well MW3-02. MW3-02 gave readings that were consistently lower than the readings of the surrounding monitoring wells therefore, the veracity of its readings is called into question. MW3-02 readings were consistently in the 8.5 m range whereas the readings of the wells on either side of it MW1-02 and MW5-02 were consistently in the 8.9 m range. Due to the well being capped the well may have been improperly vented. In this circumstance, the air pressure in the well may have artificially reduced the water levels thereby biasing the readings of the pressure transducer low.

Table 6 provides the RMSE for each of the calibration stress periods. The target 10% RMSE goal is given for each stress period. This value was determined by taking 10% of the total head difference between the highest and lowest water level measurements for each stress period. The original RMSE values are given which included the entire data set. The modified RMSE values were determined from the data set after the model was run with MW3-02 removed. Figures 16 and 17 show the calibration plots for each of the calibration stress periods (MW3-02 removed).

Table 6: Calibration Root Mean Squared Errors

Stress Period	Target 10 % RMSE (m)	Original RMSE (m)	Modified RMSE (m)
1	<0.14	0.14	0.11
9	<0.11	0.19	0.17
14	<0.11	0.20	0.17
21	<0.13	0.17	0.13
23	<0.12	0.15	0.11
41	<0.11	0.16	0.13
57	<0.13	0.20	0.16
61	<0.12	0.17	0.17

MW3-02 was originally included in the calibration but the 10% criterion could not be attained. Therefore because the readings were believed to be biased low MW3-02 readings were excluded from data set for the determination of the RMSE for each calibration plot and the calibration improved substantially. When MW3-02 was included only one of the eight calibration plots (stress period 1) met the 10 % criterion. When MW3-02 was removed three of the eight (stress periods 1, 21, & 23) met the criterion. While still not perfect, removing MW3-02 improved the RMSE on all calibration plots except for the final stress period 61 for which the RMSE did not change.

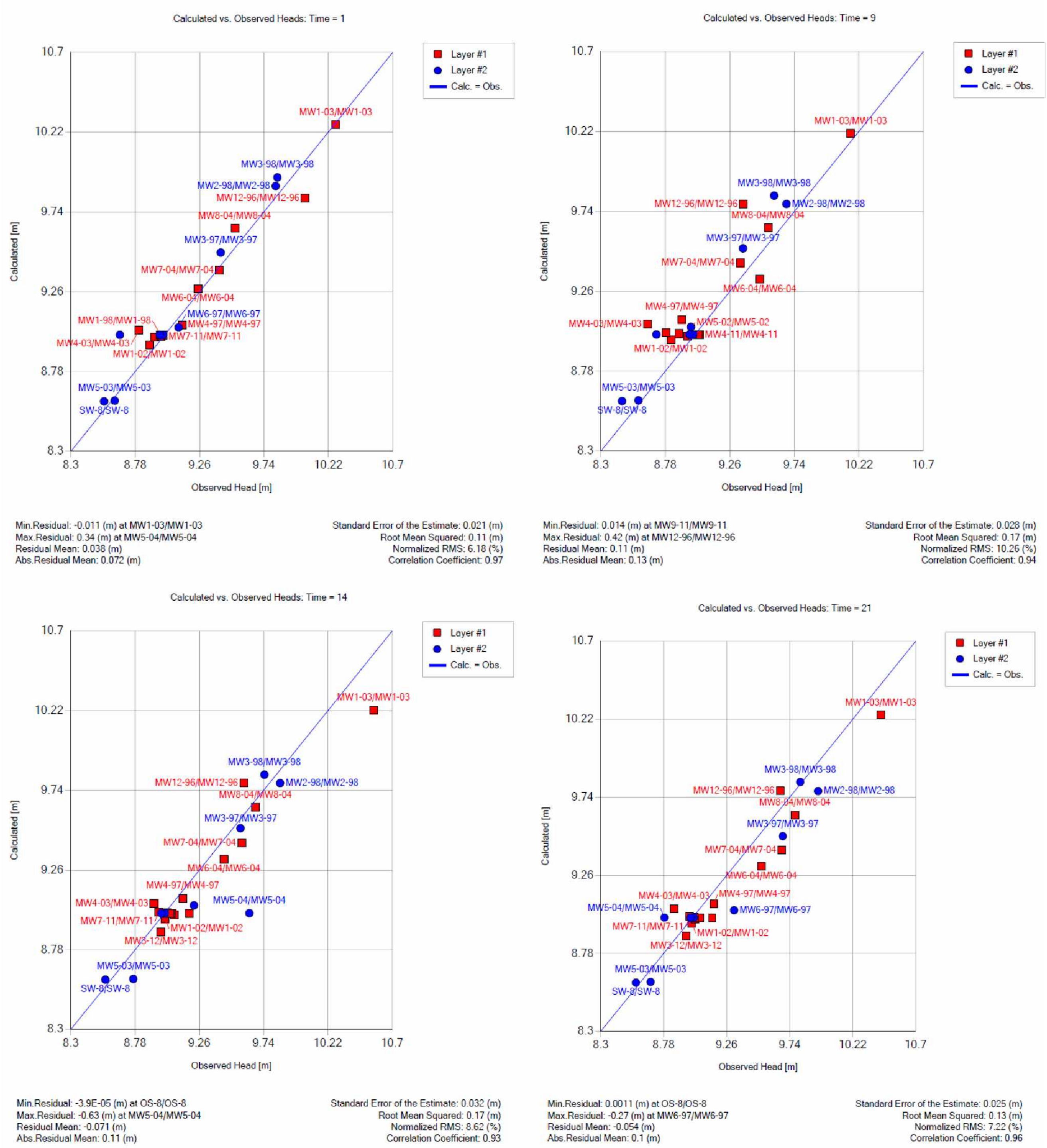

Figure 16: Calibration Plots - Stress Periods 1, 9, 14 & 21

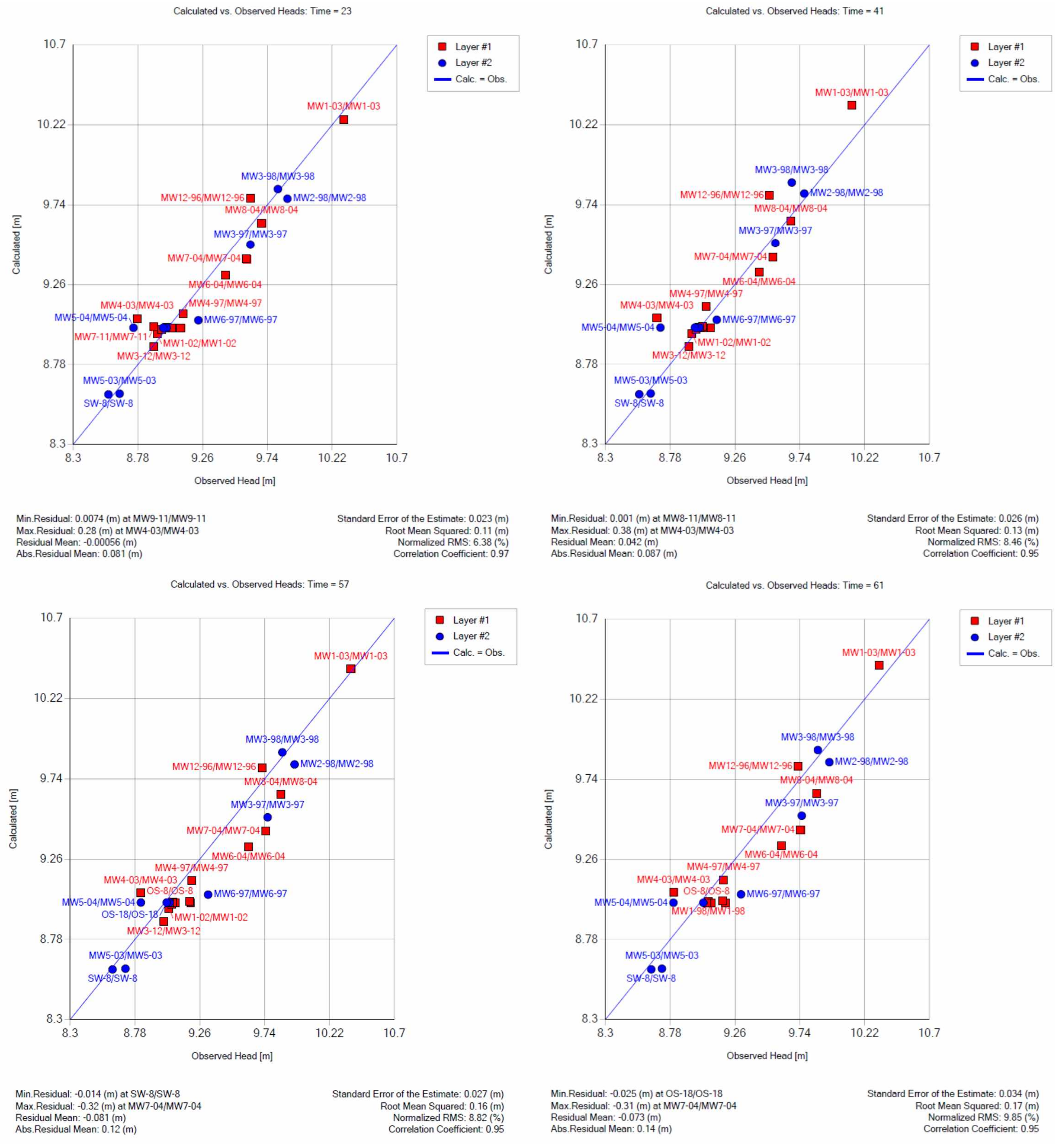

Figure 17: Calibration Plots - Stress Periods, 23, 41, 57 & 61

4.2 System Water Balance

One of the most immediately significant features of the system which the water balance in the model shows is that the overall water volume within the pad slowly declines throughout the course of the season. The pad slowly drains its stored water into the surrounding tundra ponds on its western and southwestern edges. When the total hydraulic contributions to the system are less than the hydraulic removals from the system, there is a net decrease in the water stored in the system. The hydraulic loss is illustrated in figure 18 which shows the cumulative net difference between the total water inputs and outputs to the system at each time step throughout the course of the season.

It is possible that the stored water in the pad at the beginning of the model is due largely to snow melt in the spring adding water to the system. In this situation, the method of hydraulic recharge is expected to be lateral subsurface hydraluic influx from the water bodies where the snow melt collects. After the initial recharge influx, the stored water in the system is then slowly released throughout the duration of the season. However without further fieldwork and monitoring to collect data, this hypothesis remains untested. Because the spring snow melt period was outside of the modeled time period spring snow melt storage was not able to be demonstrated by the model other than by the high initial head water levels at the beginning of the modeled period. In an earlier study, Overbeck (2015) observed lateral influx of stored snowmelt water in a study on the Kuparuk River watershed. In that study, two portions of the watershed being studied exhibited large lateral inflows during the summer months and minimal hydrologic response to precipitation. Overbeck (2015) attributes this phenomenon to snowmelt water initially stored in lower gradient terrain being slowly released over the course of the summer into the drainage network.

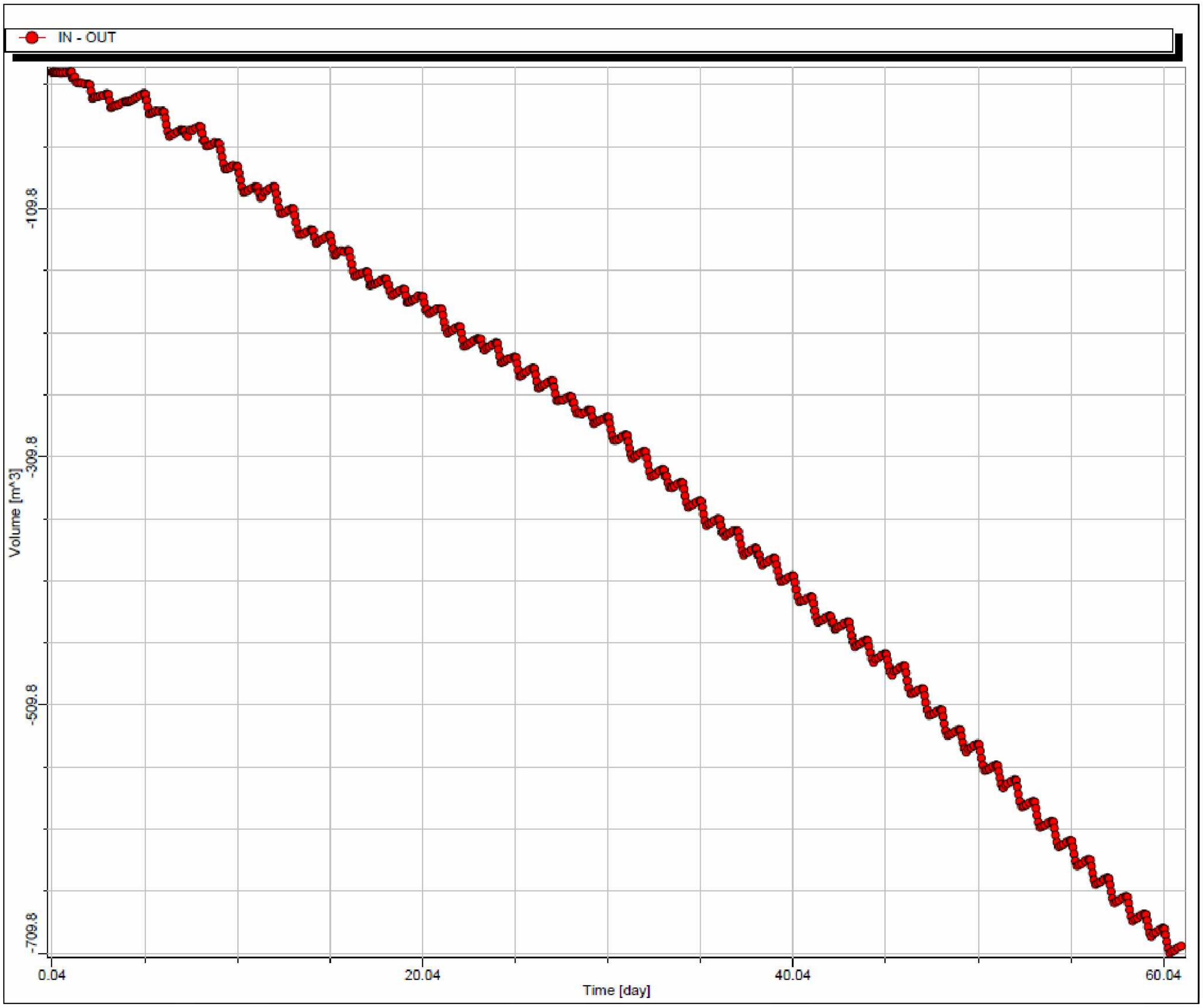

Figure 18: Cumulative Net System Hydraulic Contributions

Another interesting feature that the water balance reveals is that the recharge boundary condition is much less significant in net water contribution to the system in comparison to the constant head and specified flux boundary conditions by which water enters through the model edges. The volume of water which enters the model through the recharge boundary is 1 – 2 orders of magnitude smaller than the volume which enters through the constant head and specified flux boundary conditions. The cumulative influence of each of the boundary conditions in the model is presented in figure 19 showing a time series of the contributions of the various model boundary conditions.

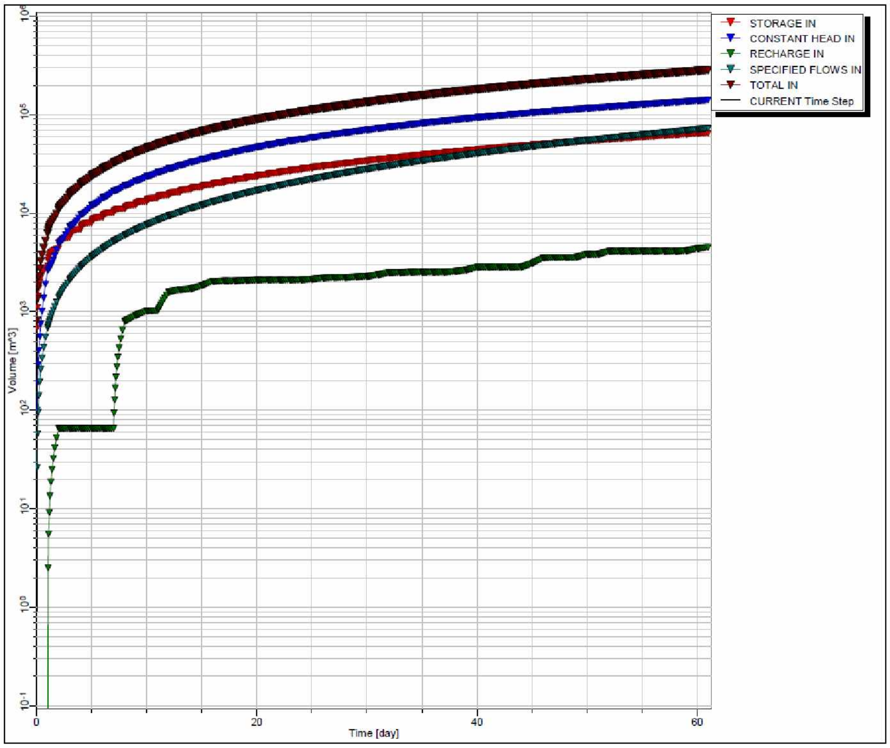

Figure 19: Hydraulic Contributions by Source

4.3 Water Levels – Contributions and Removals

One of the major features of the system which the model helps identify are what the major hydraulic contributors and removers from the COTU pad are. The boundary conditions of the model can be considered to provide information about how water is entering and exiting the system. The influence of the boundary conditions on the model can be most directly observed in relation to their impacts on the water table the model generates. From the model, changes in the water table can be observed throughout the course of the season. The water table over the course of the season changes but not very dramatically. The difference between the water table at the beginning and the end of the season can be seen in figure 20 which compares the two.

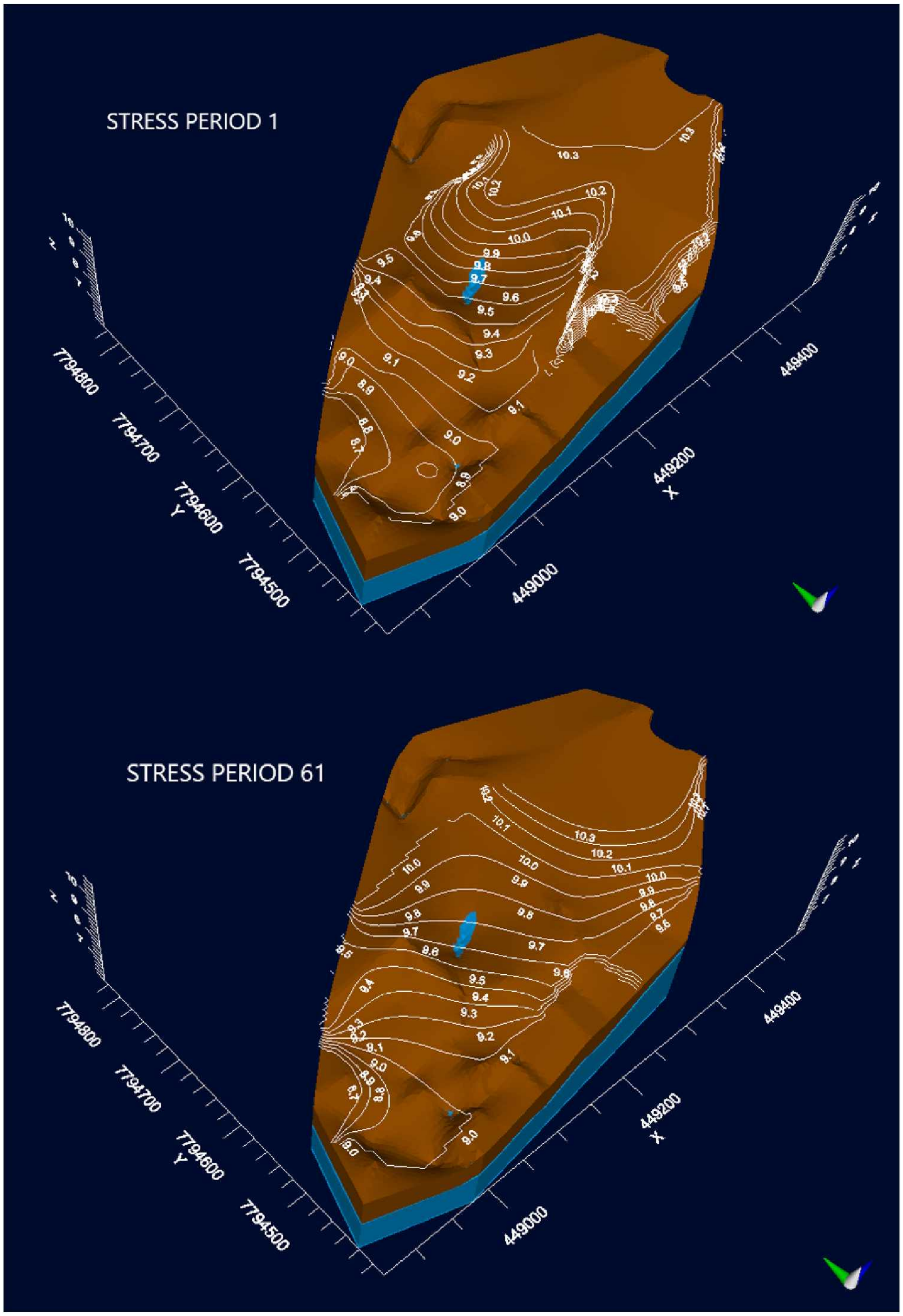

Figure 20: Modeled Water Table Changes

One of the most notable changes from the beginning to the end of the season is the drop in the water level in the southeastern portion of the pad. The high water levels in this portion of the model at the beginning are not believed to be representative of the true conditions because that area was outside of the initial heads boundary surface. Therefore, a high initial water level of 10.3 m has been used on that end of the pad since it is the upgradient portion. At the beginning of the model, it is likely there is too much water in the system in this portion. As the model time progresses, the water table on the southeast end stabilizes and comes to a more natural gradient. It should be also noted that in the upgradient portion of the pad the water table shifts from a western trend towards a more southern trend over the duration of the modeled period.

The water table can be considered in its relationship to the boundary conditions of the model, which are the hydraulic contributors and removals into and out of the system. The most upgradient portion of the water table generated follows along the edge where the specified flux boundary condition was applied. The specified flux then is the primary contributor of water to the model. The constant head boundary conditions along the other edges act primarily to remove water from the system. The constant heads along the southwest portion of the model remove water from the system out into the tundra ponds along those edges of the pad. The constant heads along the south eastern portion of the pad although not in direct contact with the edge of the gravel pad do the same, pulling water out of the model in that direction. The constant heads along the northern edge of the model show that a substantial amount of water leaves the system through the drainage ditch in that portion of the model.

Chapter 5 Discussion

The results of the COTU groundwater model reveal a number of interesting features of the pore-water movement through the gravel pad structure. The model shows how the boundary conditions on the edges of the pad may impact the hydrology within the pad. Moreover, the model has helped more clearly define the flow patterns through the pad and their relationship to the original surface topography of the native soils. Finally, it has helped develop our understanding of the areas where the water is entering and exiting the system. These results can be used to demonstrate some of the potential hydrologic impacts of different DR&R options on the hydrology.

5.1 COTU Hydraulic Sources

To get the hydraulic gradient and flow patterns observed in the model, there must be an influx of water from the northeast portion of the system from a location beyond the edge of the model. In a future study an investigation could be conducted to further determine the source of the water. For this study, insufficient data was available to make a determination of the source of the water entering the system. According to the model, the upgradient portion is on the eastern end, so water must enter the system from that direction. The source of the water remains unknown without further field study and investigation. The majority of the water that enters the model is stored already within the pad, and enters along the northeastern boundary through the specified flux along the northeastern edge of the model.

One potential source is water entering from the tundra lakes on the edges of the pad on the northern and eastern ends beyond the extents of the model. On each end of the model, digital elevations of the surrounding tundra lakes were examined from the University of Minnesota's Polar

Geospatial Center Arctic DEM Explorer. *(UMN Arctic DEM, Porter et. al., 2019 – https://www.pgc.umn.edu/data/arcticdem/)* According to the Arctic DEM data, the surrounding tundra lakes are at roughly 6 – 7 m amsl elevations which are lower than the heads in the eastern end of the model which are 10 – 11 m amsl. Therefore the lakes on the eastern end are not believed to be a dominant source of the water influx. Figures 21 and 22 show cross sectional elevation profiles from the Arctic DEM Explorer from each end of the COTU facility.

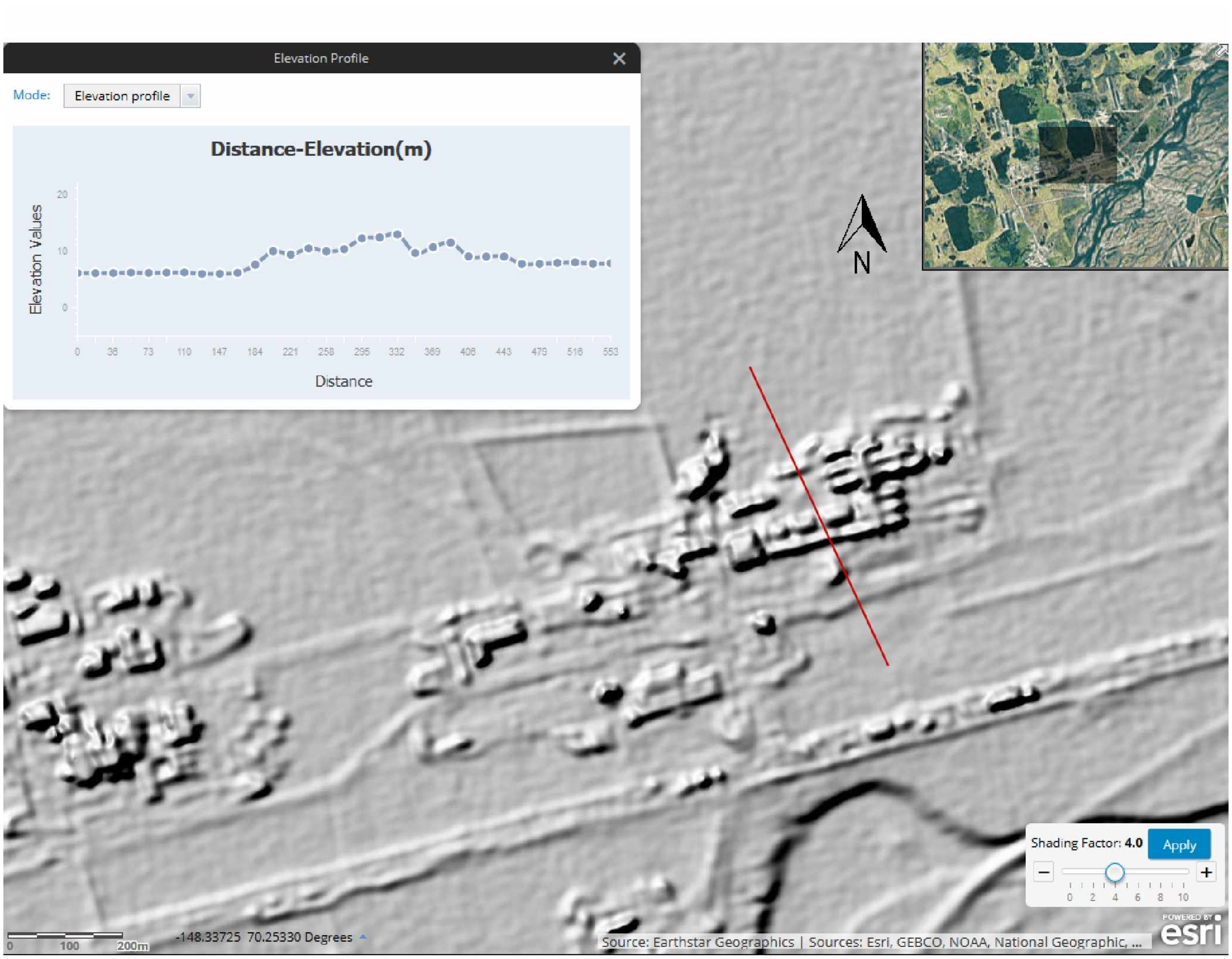

Figure 21: COTU Eastern Cross-Sectional Elevation Profile - Source: UMN Arctic DEM, Porter et. al., 2019 (https://www.pgc.umn.edu/data/arcticdem/)

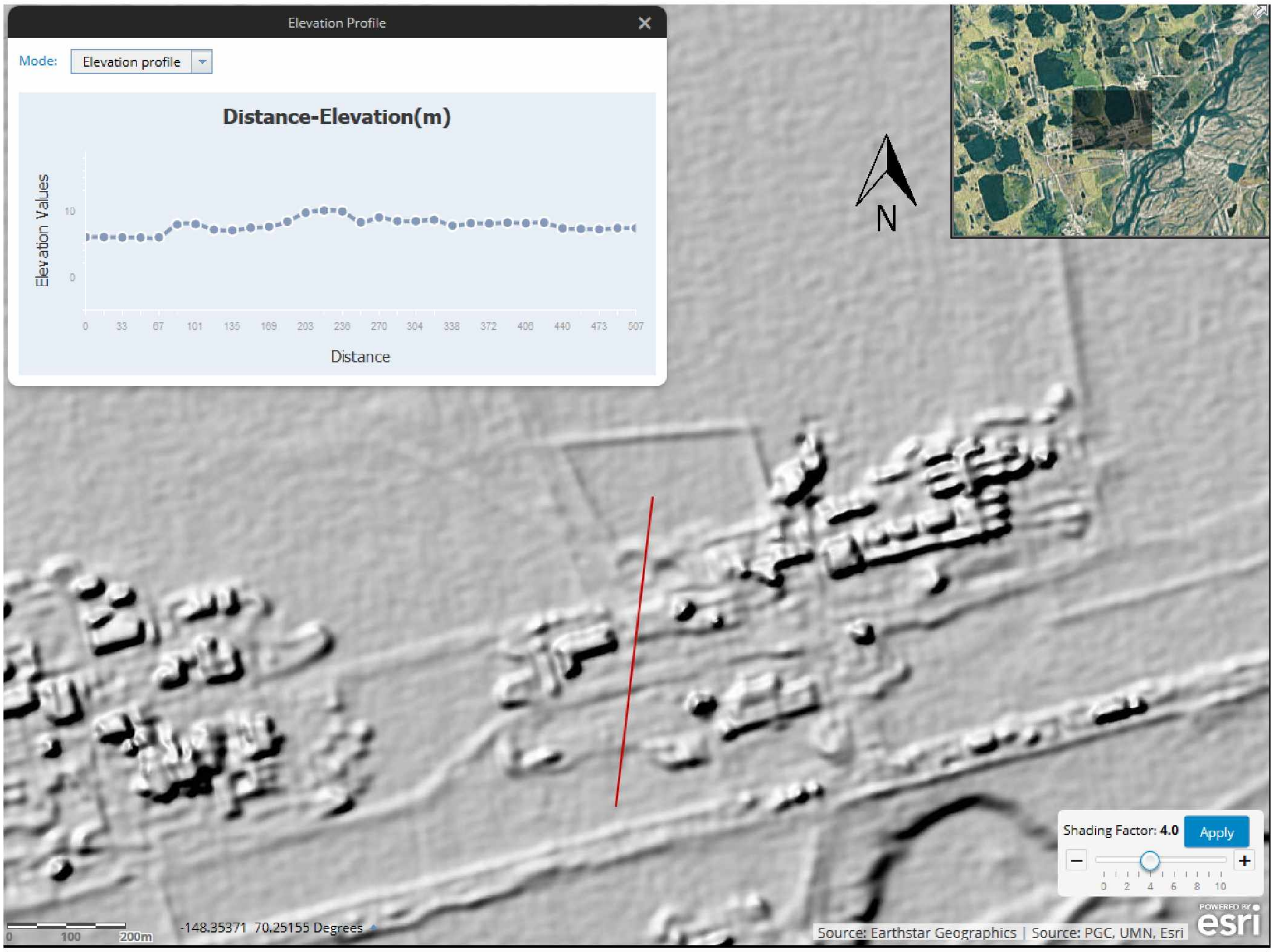

Figure 22: COTU Western Cross-Sectional Elevation Profile - Source: UMN Arctic DEM, Porter et. al., 2019 (https://www.pgc.umn.edu/data/arcticdem/)

A second potential source considered is precipitation. From the water balance of the model however, precipitation seems to have a small effect on the overall hydrologic character of the system. The system is much more controlled by the constant head boundary conditions and the specified flux boundary condition as opposed to the recharge boundary condition applied on the top. Except for a few isolated rain events, the recharge has an almost negligible impact to the overall water balance of the system. The volume of water that enters the model from the precipitation boundary condition is much smaller than the volume of water that enters through the other boundary conditions. Therefore, precipitation is not considered to be be a dominant factor influencing the hydrology of the system. This result is contrary to the initial hypothesis of the Barnes (2014) study which was that the precipitation would have a much more significant impact on the overall hydrology.

Ultimately without additional data from further fieldwork investigation, the specific source of the water entering the COTU cannot be determined in this modeling study. The majority of the water in the model comes from the influx of water which is already stored within the pad. How this water initially enters the pad is an unknown, which the model is unable to tell us. It is believed to enter the system somewhere on the northeastern end which is the upgradient portion of the model. Beyond this little may be concluded about where the water in the system is coming from.

5.2 COTU Flow Patterns

In the COTU model, the flow patterns through the pad were traced using the USGS MODPATH particle tracking feature *(Harbaugh, 2005)*. 67 total particles were placed along the northeastern upgradient edge of the model, one in each cell and their flow paths traced over the duration of the modeled period. Figure 23 shows the particle paths and the resulting subsurface flow patterns and their relationship to the surface infrastructure on the pad. The hydraulic gradient shown in figure 23 is from stress period 61 at which point it is believed the gradient in the model has most stabilized. The hydraulic gradient is inherently always dynamic, however later on in the season the amount of change between stress periods decreases substantially. Therefore stress period 61, the final stress period of the model was selected.

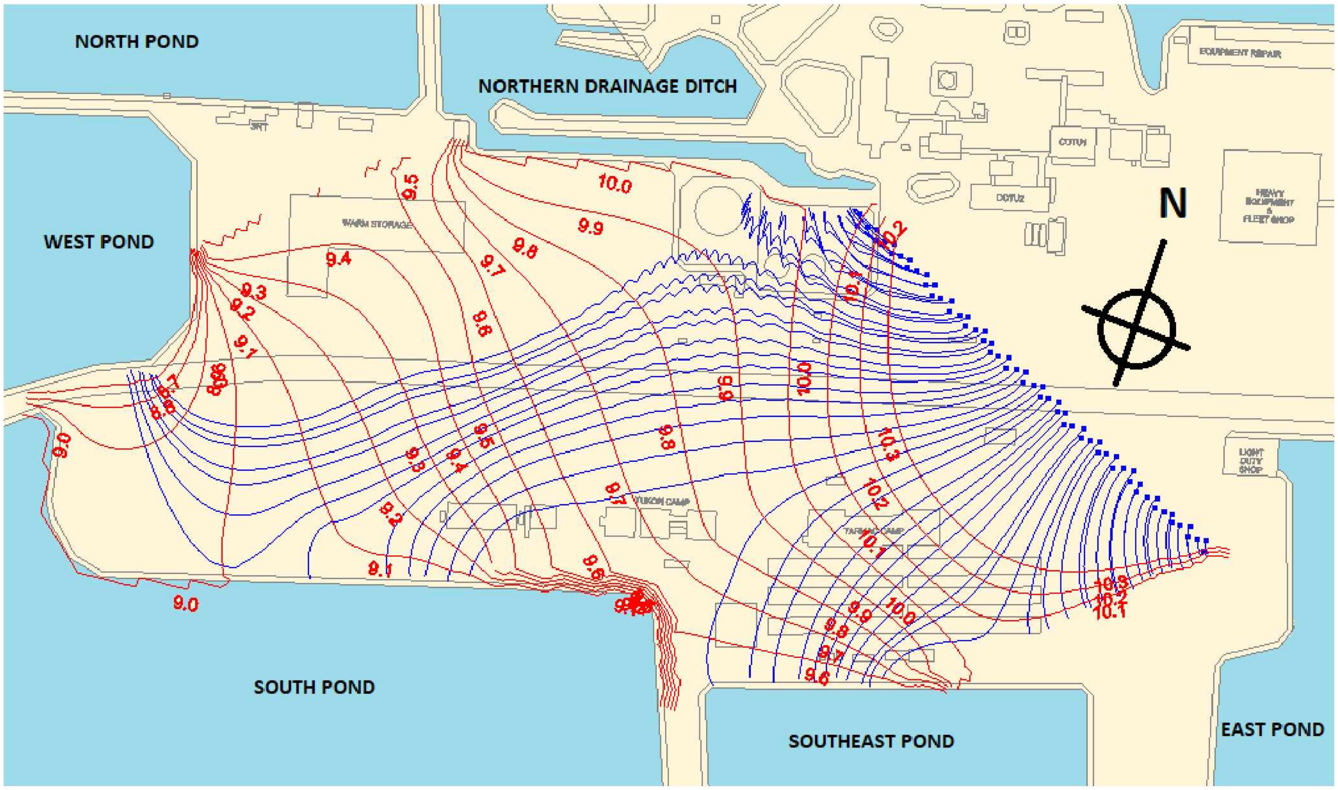

Figure 23: COTU Hydraulic Particle Trace – Stress Period 61

From this figure, it can be observed that the flow paths exit the pad in four principle areas. The northern drainage ditch, the west pond, the south pond, and the southeastern pond. The north pond and the east pond may also have an influence on the pad hydrology as well although none of the flow lines were traced directly to them. Both of the ponds were beyond the extents of the model. Standing water can be observed in each of these areas in aerial imagery. A total of 67 particle flow paths were traced through the model. The distribution of the 67 particle exit paths in the four identified areas is given in table 7.

Table 7: Drainage Paths

Exit Area	Particle Paths Lines	Path %
Northern Drainage	21	31.4 %
Western Pond	7	10.4%
Southern Pond	6	9.0%
Southeastern Pond	11	16.4%
Indeterminate	22	32.8 %

Although the percentage of the flow paths does not give us precise volumes of water exiting into each of these respective areas, it does provide a rough idea of where the majority the water is leaving the system. Most of the flow lines exit the system in the upgradient portion of the pad prior to ever reaching either the western or southern edge ponds. It is unknown where the upgradient water leaving the system ultimately ends up. Without further field investigation, the model cannot provide us with this information.

Based on the flow lines distributions, the northern drainage ditch creates a very strong hydraulic gradient in the system towards it. The hydrologic influence of the northern drainage ditch can be observed even in the some of the nearby flow lines that do not exit through it directly. They are redirected in the direction of the ditch before resuming their prior path through the center of the pad. Without further data it cannot be determined what is causing the strong hydraulic gradient towards the ditch, although it is likely the flow path is a result of the original silt topography. Despite the lack of conclusive data in that area, the impacts on the modeled hydrologic topography of the water table may still be observed.

The southeastern pond also has a strong hydraulic influence on the system, however the flow through leaving the system through this area may be due largely to the contours of the silt topography directing flow that direction just as much as the strength of the hydraulic gradient from the boundary condition. One significant result that should be noted is that the southeastern drainage pond area is significantly more flooded on its southwestern end than on its northeastern end. The flow patterns exiting through that portion of the pad are concentrated in the southwest where the majority of the surface water can be observed. This can be seen in figure 24, which illustrates the flow patterns over the satellite imagery of the pad.

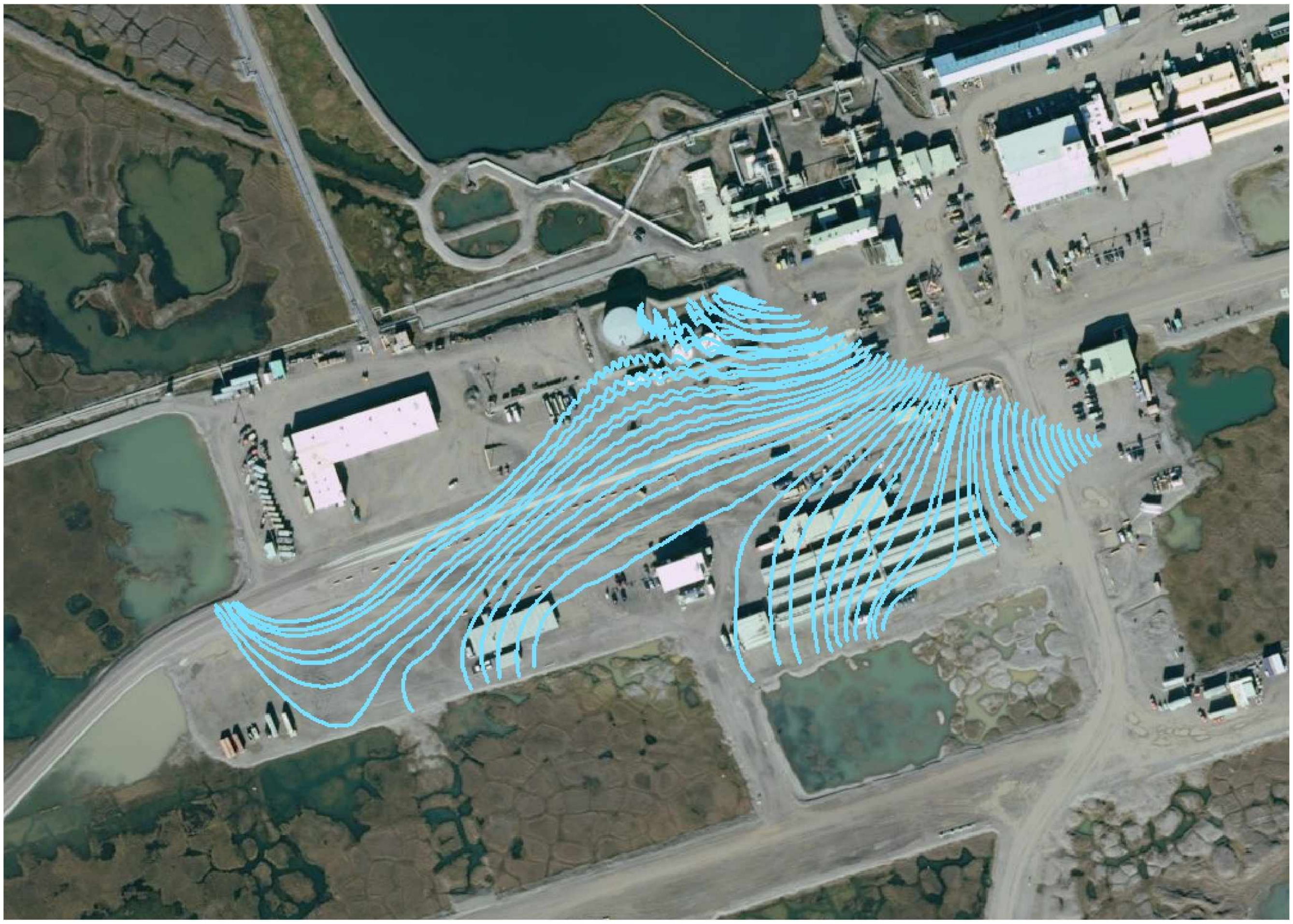

Figure 24: Flow Patterns Through the COTU

As figure 24 illustrates, most of the drainage out of the model occurs in the upgradient portion, therefore the downgradient ponds cannot be predominantly receiving their water from the pad. The western and southern ponds are likely receiving most of their water from external hydraulic sources beyond the model to the southwest. There are other surface water bodies in the southwest direction which may be feeding into the ponds in this area.

On the most eastern end of the modeled area, there were 22 hydraulic flow lines that were unable to be traced to any of the four principle pad drainage areas because they reached the end of the modeled area before the edge of the pad. It is likely they ultimately either end up in the southeastern drainage pond area or are drawn off the eastern edge of the pad. Without more data and field work in this area the model is unable to tell us what the flow patterns are ultimately like in this portion. The properties in that area are also highly uncertain as well. Therefore, the flow patterns produced on the far eastern end of the modeled area are questionable in their veracity to actual site conditions.

One interesting feature of the modeled flow patterns that should be noted is that the flow pattern in the southeastern portion of the model travels directly underneath a large group of buildings on the pad. In theory, because of solar shading these buildings may limit seasonal thaw beneath them. If they do, the flow patterns might be directed around the frozen soils in this area which will be at a topographical high in comparison to the permafrost in the surrounding areas of the pad. Due to insufficient data, the model was not able to show whether this is or is not occurring in that portion of the pad.

5.3 Subsurface Silt Topographical Influence on Flow Patterns

As determined in the Barnes (2014) study, the topography of the underlying silt surface strongly influences the flow dynamics within the pad. The reason for the strong silt topographical influence is because the hydraulic conductivity of the silt is much lower than that of the gravel. Therefore, the flow tends to follow the path of least resistance through the gravel over the silt topography. The topography of the subsurface silt is a significant factor causing the overall northeast – southwest gradient seen in figure 24. The general topographical character is that the silt surface has a generally higher elevation in the northeast and lower elevation in the southwest. Therefore it follows that if the groundwater is following the sub grade silt topography it should be expected to also move towards the lower elevations in the southwest which is exactly what was observed in both the Barnes (2014) field study and in the model.

The groundwater movement in both the field study and in the model appears to follow roughly the flow channels where the tundra lakes existed prior to placement of gravel on the tundra surface. The flow channeling modeling result is reasonable because the water is expected to preferentially flow through the areas where the gravel has a higher hydraulic conductivity than the surrounding native silts. The flow channeling phenomenon can be seen in figure 25 which shows the subsurface flow patterns through the pad over the silt topography.

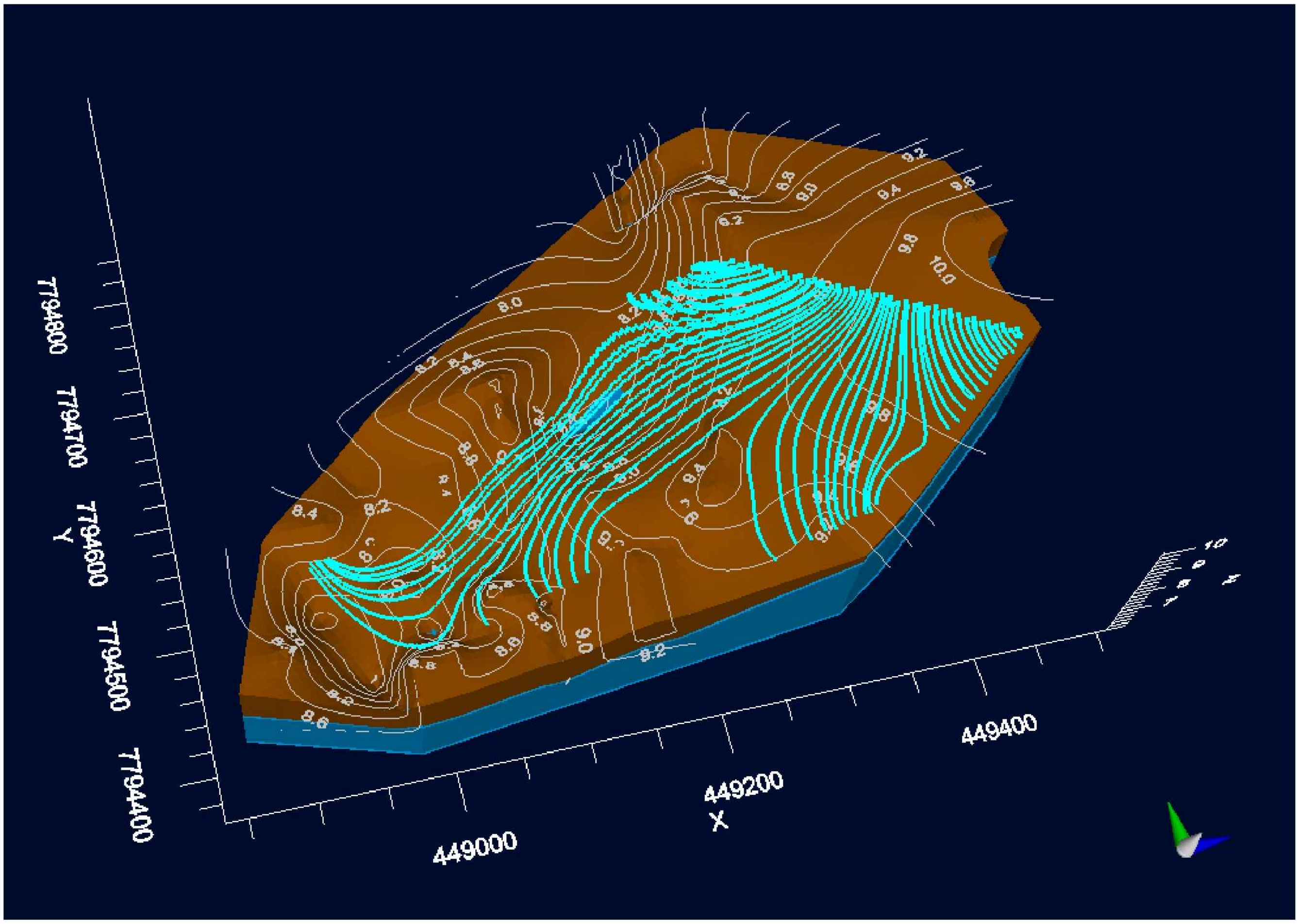

Figure 25: Flow Patterns Over Silt Topography - Exaggerated 35 Times

It can be seen that the flow routes around the silt topography at three key locations in the model where the flow patterns clearly diverge from one another. The first location is on the northern edge where the flow gets drawn aside into the drainage ditch. The second location is in the middle of the pad where the flow channels around the high point of the silt topography. The third location is at the bottom of the flow before it exits into the southwest and southern ponds. The flow redirection is a direct demonstration of the flow channeling phenomenon by which the flow follows the subsurface topography of the silt. In another study, Carlson and Barnes (2011) found a similar result in a discontinuous permafrost aquifer. There researchers showed the strong influence the top of the permafrost topography has on groundwater flow directions in these types of aquifers.

The COTU model demonstrates that the most influential factor controlling the subsurface hydraulic flow patterns is the topography of the silt beneath the pad. Because the silt has a much lower hydraulic conductivity than the gravel, the water flows through the gravel preferentially around the high points of the silt topography. The silt topography is much more influential to the hydrology than the off pad water bodies such as tundra ponds. There is not enough water in the system to have strong hydraulic influences from lakes or other water bodies such as might be seen in other natural hydraulic systems. The permafrost beneath the shallow active layer acts as an aquitard preventing water flow beneath it. This causes the unfrozen soil to become quickly saturated by the water in the system and all subsequent flow therefore takes place over the silt topography. Because of the overall low amount of water in the system and the shallow permafrost table the water movement is more strongly influenced by the silt topography than any other hydrologic parameters.

5.4 Implications For DR&R Strategies

As discussed, the four DR&R strategies being considered for the Coastal Plain gravel pads are full gravel removal, partial gravel removal, revegetation and leaving the pads in place. The hydrological aspects of DR&R operations may be considered both specifically for the COTU facility as well as generally for gravel pad infrastructure across the Arctic Coastal Plain. The specific hydrological implications of the COTU model for DR&R may be used to inform the general hydrological implications of DR&R at other facilities across the Arctic Coastal Plain, although specific site conditions will vary from location to location.

5.4.1 Hydrological DR&R Implications For The COTU Facility

If DR&R were to take place at the COTU facility, a number of it's hydrological features should be taken into consideration. The upgradient portion of the pad is towards the northeastern end. Therefore, if any portion of the gravel is removed from the northeastern end, the flow through the rest of the pad could be dramatically impacted. Any changes in flow patterns could have a dramatic effect on the thermal stability of the COTU pad. Water movement is one of the primary heat transfer mechanisms in the Arctic because of its high capacity to move thermal mass. Therefore, if flow patterns are shifted due to gravel removal, then the thermal regime may be altered as well. When the thermal regime changes, this often results in thawing of permafrost which was previously stable. When the permafrost thaws the topography changes and more water is allowed to collect in the new tundra ponds thus perpetuating the cycle. If the stability of the permafrost is compromised, the structural stability of the gravel pad may be compromised with it.

In the model, the COTU pad is storing and moving much of its water through the gravel following the subsurface depressions in the silt topography. If gravel is removed from the areas of lower silt topography, then these storage and flow areas will be impacted. Most likely they will experience even higher water movement through them. If gravel is removed from the areas of high silt topography, then the subsurface flow patterns may be effected some but not shift as much as in the lower silt areas.

Overall however, it should be considered that it is the silt topography not the gravel which is the driving factor in controlling subsurface flow patterns. It is possible that if only a portion of the gravel is removed then flow patterns may not be effected directly the removal at all until the excavation drops the surface elevation below the water table at which point new surface water bodies will be formed. Flow patterns may be effected indirectly however by the resulting permafrost degradation from loss of insulation.

As long as the system is not flooded, the COTU pad retains much of its water in the subsurface silt depressions particularly on the southwestern end. These depressions may also retain contaminants within them preventing them from leaving the pad and entering the surrounding arctic wetlands. Gravel removal operations may be conducted with flow channeling in mind to preserve this natural protective feature of the pad. It should be noted, that if the hydrology is impacted in such a way that the system is inundated with water, the contaminants may be flushed out of the subsurface depressions and leave the pad. Therefore if possible, flow pathways should be intentionally developed to channel water away from the depressions so that they are not flushed out onto the wetlands. Even if the depressions are maintained, this is not a permanent solution to gravel pad remediation because natural attenuation processes in the arctic are extremely slow if they work at all in many cases. Therefore, if contaminants are collected in subsurface depressions, they must eventually be dealt with and cannot be allowed to remain permanently in the environment.

5.4.2 General Hydrological DR&R Implications

If any portion of the gravel is pulled out whether partially or in full, the subsurface permafrost will be exposed, which if not reinuslated will result in thermal degradation. Normally, the Arctic landscape is covered by an organic vegetation mat that helps provide insulation. However, the construction of the gravel pads has destroyed this layer underneath them which cannot be easily regrown. Therefore, if the gravel is removed, the native soils will be left exposed without insulation. In ice rich permafrost areas most likely significant ground thaw subsidence will result. Water will collect in these areas forming new tundra ponds promoting thermokarsting.

If as part of the DR&R operations, flow patterns must be intentionally changed, the best manner to accomplish this change is by altering the topography of the subsurface silt in order to redirect the flow. This could be most easily accomplished through direct excavation. It should be remembered though that exposed silt will be unprotected from thermal degradation.

If any portion of the gravel is removed, most likely it will need to be in the areas that are contaminated with petroleum or other industrial chemicals. In these areas unless the excavations are backfilled new surface water bodies will form. The backfilled material must have a lower thermal conductivity than the excavated material or else thaw subsidence may still result. In a prior study Barnes (2015) found that in such cases, coarse grained aggregates such as the gravel used to construct the pads had a higher thermal conductivity than that of the silts of the native material. Because of the higher thermal conductivity, even if gravel is used as backfill material thermal degradation of the frozen soil will still result. Barnes (2015) recommends that gravel may still be used as backfill material while applying a layer of at least 0.5 m of native silt soil as cover to allow for adequate thermal insulation to prevent frozen soil degradation. This method allows for the gravel to be reused while minimizing both the amount of native soils required for thermal insulation backfill and the impacts to the thermal regime of the frozen soils.

If the pads are left in place, they will slowly erode naturally due to lack of maintenance. The edges of the pads will undergo rotational failure. Over time the native vegetation will reclaim the structures however this may be a centuries long process. The gravel pad structures will permenantly exist as new features of the landscape of the Arctic Coastal Plain of Alaska. Because of gravel's higher storage capacity than the arctic tundra, the gravel pads have the potential to store within them a great deal of water making them tremendously impactful on arctic hydrology. The model demonstrates the storage of free water within the pad over the course of the summer of 2013. If these pads are left in place, they will continue to act as subsurface reservoirs for groundwater.

Chapter 6 Conclusions

Over the last 50 years due to the oil developments, an immense amount of gravel material has been placed onto the surface of Alaska's Arctic Coastal Plain. Modeling the groundwater flow through the COTU pad in this study has helped develop an understanding of the impact this placed gravel has had to the hydrology of the Arctic Coastal Plain. By constructing the model, this study was able to examine the water movement through the COTU pad over the course of the summer of 2013. When considering DR&R alternatives, it is critical that both legislators and leaders in the industry take into consideration the hydrological implications of all considered options. The findings of this study are useful to both legislators and leaders in industry because they provide further knowledge and insight into the hydrology of the gravel pad structures and their hydrological effects on the Arctic Coastal Plain environment, as well as the hydrological implications of their remediation.

6.1 Major Findings and Results

The Barnes (2014) field study originally hypothesized that the precipitation would be one of the dominant factors in the hydrology of the gravel pad. Although precipitation is one of the primary driving factors of arctic hydrology on the Arctic Coastal Plain, in the model the effect of the precipitation recharge boundary condition was minimal. In the model, the precipitation was too low in total water volume contribution to the system in comparison with the other boundary conditions in the model to be significantly influential. Although singular precipitation events throughout the summer resulted in minor changes to the water table in the model, they had very little long term impact on the system as soon as the precipitation ceased. It should be noted however, that the precipitation contributed as a major input to the tundra ponds around the model which were the determining factor for the heads of the constant head boundary conditions. Therefore, the precipitation although not significantly influential on the model directly, did have an indirect impact on the model through its influence on the ponds which determined the model edge boundary conditions.

The Barnes (2014) study did hypothesize that the pad pore-water movement was strongly influenced by the topography of the silt beneath the pad. This channeling effect was able to be observed in the results of the model. The model has helped expand upon the results of the Barnes (2014) field investigation providing details about the pad hydrology which the field study on its own was unable to produce.

The model also demonstrated that the tundra ponds off the edges of the pad act primarily to create a hydraulic gradient out of the system rather than contributing water to it. The constant head boundaries around the edges of the model removed more water out of the system than they contributed in. The conclusion then is that because the tundra ponds are at lower elevations, they create a hydraulic gradient out of the pad as opposed to into it. At the COTU pad, the tundra ponds adjacent to the modeled area were determined not to be the source of the water entering the system. The source of the water in the system remains an unknown which was not able to be determined in this study. Precipitation is too low to contribute the volumes of water observed in the model, and the tundra ponds are at too low of elevations to bring water into the pad. Because only the southwestern portion of the pad was modeled, the primary hydraulic source of the water was not able to be determined. The water is believed to be primarily entering the system in the northeastern end which is beyond the extents of the model. In the model, the main source of water in was the specified flux boundary condition, however this was intended to simulate the influx of water into the model which was already stored within the pad. It does not provide us with any indication of the ultimate source of the water entering the system.

What the model did show about the hydrology was that the most significant controlling factor in the pad hydrology was the topography of the subsurface silt below the pad. The soil has a very shallow active layer. Within the active layer the silt and organic soils above the permafrost quickly reach saturation because of the permafrost below. Once the water levels exceed the saturated thickness of the silt and organics, the water flows through the gravel following the contours of the subsurface silt topography. The flow is redirected around the high portions of the silt topography and is channeled through the low areas where the tundra ponds and lakes existed prior to the construction of the gravel pad.

6.2 Future Research

A future hydrologic study of the COTU pad should concentrate on acquiring more data from the northeastern end of the pad where the Barnes (2014) study lacked. Based on the results of the field study and the modeling, the most significant data which could be collected would be geotechnical boring logs in order to get an accurate representation of the silt topography of the pad since the silt topography is the hydraulically controlling factor. If possible, water levels would be valuable as well, particularly in area just to the east of the model. Specifically, more water levels from the adjacent ponds and lakes would be useful. If the model were to be refined, better water level data towards the eastern end could significantly improve the model, especially towards the beginning of the modeled period when the initial heads play a significant role in the hydrology. The model could also be redeveloped with more current data using the same structure but with more current water level and precipitation readings. In a future study, a slug test to obtain the hydraulic conductivity of the gravel and of the silt would be useful as well. The modeled hydraulic conductivity of both the gravel and the silt which were purely empirically established through trial and error could be compared to the results of the test.

The focus of a future field study would likely be towards determining the source of the water entering the pad. The Barnes (2014) field study and the COTU model have revealed that the pad drains its water to the surrounding ponds and lakes over the course of the season, and that the silt is a controlling factor in the flow paths, but they have been unable to determine the source of the water entering the pad. Future field work should focus on answering this question, determining where the water in the pad is coming from. In this study, because the entire COTU pad was not able to be modeled, the influence of all the surrounding water bodies was not able to be identified. Although it is not believed that any of the COTU surrounding water bodies are at a high enough elevation to be significant contributors to the system, the model and field study are unable to demonstrate their influence. Future research may be directed towards determining if tundra ponds can act as hydraulic contributors or if the trend of hydraulic removal out of the system observed in the COTU model and field study is common to most.

6.3 Hydraulic Implications for DR&R Operations

Any DR&R activities in the Arctic Coastal Plain should take into consideration the hydraulic impacts that they may have on the landscape once they are complete. Because it has been determined that the silt topography is the controlling factor in the hydrology through the gravel pads, it is the recommendation of this study that any DR&R activities undergone should have a thorough geotechnical investigation conducted prior to DR&R operations in order to understand the nature of the silt topography. Identifying the low points of the topography will lead to a better understanding of the hydraulic flow channel pathways which the water movement is likely to follow. This will then lead to better decision making in regards to what to do with the gravel from the facilities.

Decision makers ought to recognize that it is the topography of the silt which controls the flow patterns of the water. Therefore, they must consider how DR&R operations may effect silt topography. This is particularly significant in that any thermokarsting which results from gravel removal will change the silt topography and thereby change the flow patterns as well. In pads that are contaminated, the impacts to the flow patterns are especially relevant because any chemicals spills which are not remediated should not be allowed to leave the gravel pads and enter the native environment. If flow patterns shift, there is a risk that chemical release may occur. If the subsurface silt topography is understood, it can be used to help control chemical spills if they can be contained within the subsurface silt depressions.

Another factor which ought to be taken into consideration is that the tundra ponds on the edges of the pad in this study hydraulically remove water out of the system because they are a lower elevations. If some portions of the gravel are removed even if the underlying silt is not exposed, this may result in changing the influence of the surrounding tundra ponds. Depending on the underlying silt topography at the site, the adjacent tundra ponds may switch from removing water out from the system to contributing water to it, thus changing the hydrology. It should be noted, that although this study did not identify any of the tundra ponds adjacent to the COTU pad as hydraulic contributors, that does not mean that hydraulic contribution will be the case at all facilities. It is entirely possible that some tundra ponds do contribute into the system rather than removing from it. It is recommended that a field study be conducted prior to DR&R operations to determine whether the surrounding ponds are contributing to or removing from the gravel pad structures prior to decommissioning.

6.4 Future of Existing Gravel Pads

If any amount of the gravel is removed, the gravel will need to be disposed in an environmentally resonponsible manner. Most likely that will mean returning it to the Sagavanirktok river or the pit mines where it was originally from, however other options may be considered as well such as material reuse at new infrastructure locations. The gravel may also be reused to intentionally construct hydrologicaly influencing structures. Water movement is one of the most influential heat transfer mechanisms to degrading permafrost. Therefore, controlling water movement should be a significant consideration of any DR&R activities. If the gravel can be used for this purpose it may be a productive way to reuse the removed material. It should be remembered though that the silt itself is more influential on the flow patterns than the gravel placed on top of it. If the silt topography is changed, then flow patterns will shift. Gravel however is not as likely to shift flow patterns so much as create subsurface storage reservoirs and slow the rate of water movement through it.

If the gravel is left in place and none is removed, over time the edges of the gravel structures will experience rotational failure similar to that often seen on road embankments. When this occurs, thermokarsting will result however most likely to a lesser degree than if the gravel were immediately fully removed. If the gravel is not removed, the question becomes what is to be done with the pads left in place? Revegetation is an option which is being explored. If the pads are left in place for revegetation they will require continued maintenance during the process or else failure will occur. In addition, due to the harsh climate and short growing season on the Arctic Coastal Plain this option may have significant challenges associated with it. Several attempts at revegetation have already been conducted at experimental DR&R sites however they have been met with very limited success. Typical results have been less than 1% vegetation cover after three years without direct intervention *(Oil and Gas Technical Report, 2014).* Revegetation is dependent on water availability for the plants to grow.

Water stored within the gravel pads may be available for this purpose. As an organic mat reforms on the gravel surface, the storage properties of the soil will gradually change over time as well influencing the hydrology of the system.

Another alternative for pads left in place is that due to coastal erosion a number of the villages along Alaska's shoreline are beginning to explore the idea of relocating to new locations. The abandoned pads may provide a potential location to which the relocating villages may consider moving. One further option is that native species such as caribou tend to congregate on the gravel structures. Therefore the pads could be re-purposed as wildlife habitat. There are always other alternatives which are not considered here, but these are a few of the major ideas being explored at present. Almost certainly, each facility will face it’s own unique challenges in the DR&R process and the solution at each site will need to accommodate the local conditions.

6.5 Final Considerations

DR&R operations will only become more and more significant of a discussion item in the near future as TAPS continues to decrease its flow. Although recent explorations and open leases in the NPRA and in the 1002 area of ANWR will help keep oil flowing for a time, eventually even these will be spent and DR&R operations must be conducted. Even before they are exhausted, the currently existing facilities must be decommissioned as production transitions to the new locations. The more infrastructure which is constructed, the more work there will be in the decommissioning process. The more thought and effort is put into it before the oil is used, the easier the process will be.

The impacts to the environment and more specifically the hydrology must be taken into consideration when conducting DR&R. Failure to do so could result in damage to the Arctic that could become permanent, such as the surface scaring which may still be seen from the early days of exploration. Although the early explorers didn't realize what they were doing or the long term impacts of the damage they did to the arctic tundra, we have the benefit of looking back and learning from them that industrial activities in the Arctic must be done in an environmentally conscious manner or else irreversible damages may result. Having had the time and experience to develop our technology, we now have the necessary tools available to us to conduct our industrial operations in a safe and responsible manner.

Although the future of the Arctic is uncertain, it does not have to be bleak. Studies such as this one can help those responsible for DR&R to make informed decisions in such a manner that the environment is most protected, while the benefit of natural resource development is still obtained. It should be remembered that the human nature relationship should be ideally to the greatest extent possible a symbiotic one of mutual benefit. We are stewards of the earth and are responsible for it's well being as much as our own.

One of the most significant components of the environment we live in is the water around us. This is particularly true on the Arctic Coastal Plain of Alaska where despite the low precipitation the water is the most prominent feature of the landscape. Therefore, our DR&R activities must take their hydrologic impacts into consideration and the effects they will have on the water of the Arctic Coastal Plain environment. Industrial developers have a responsibility which they must take seriously to maintain and care for the water resources in the Arctic and on Alaska's Arctic Coastal Plain.

Water, being critical to the well being of the arctic environment, should be on the forefront of our minds in any activities we undergo for industrial development. Although we do not often realize it, we have a constant relationship to the water around us which can be either positive or negative. We drink it in, we flush it out, we work with it, we play with it. Water is a source of life and we are dependent upon water in every aspect of our lives.

Although final determinations of what to do with the gravel pads have yet to be made, this study has provided insight into the potential hydrologic implications of some of the strategies being considered. Through the modeling efforts of this study the impacts of the placed gravel to the sensitive hydrology of the arctic environment are more well understood. There will always be more questions which can be answered but the model has at least advanced our understanding of the impacts of the existing infrastructure. Although we will never be able to answer every question, this study has furthered our understanding of the hydrology such that responsible decisions regarding DR&R operations may be made.

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Appendix A – Operating Units Summary

Data provided courtesy of Alaska Department of Natural Resources

UnitName	Status	Administration	Operator
Arctic Fortitude	Terminated	State	
Badami *	Active	State	Savant Alaska LLC
Bear Tooth	Active	Federal	ConocoPhillips Alaska, Inc.
Beechey Point	Active	State	Brooks Range Petroleum Corporation
Colville River *	Active	State/Federal/Native	ConocoPhillips Alaska, Inc.
Cronus	Terminated	State	
Dewline	Terminated	State	
Duck Island *	Active	State	Hilcorp Alaska LLC
Greater Mooses Tooth *	Active	Federal	ConocoPhillips Alaska, Inc.
Guitar	Active	State	Alliance Exploration, LLC
Kachemach	Terminated	State	
Kavik	Terminated	State	
Kuparuk River *	Active	State	ConocoPhillips Alaska, Inc.
Kuukpik	Terminated	State	
Liberty	Active	Federal	
McCovey	Terminated	State	
Milne Point *	Active	State	Hilcorp Alaska LLC
NE Storms	Terminated	State	
Nikaitchuq *	Active	State	Eni US Operating Co. Inc.
Nikaitchuq North	Active	Federal	
Northstar *	Active	State/Federal	Hilcorp Alaska LLC
Oooguruk *	Active	State	Caelus Natural Resources Alaska, LLC
Pikka	Active	State/Native	Oil Search (Alaska), LLC
Placer	Active	State	ASRC Exploration LLC
Point Thomson *	Active	State	ExxonMobil Alaska Production Inc.
Prudhoe Bay *	Active	State	BP Exploration (Alaska) Inc.
Putu	Terminated	State	
Qugruk	Terminated	State	
Rock Flour	Terminated	State	
Sakonowyak River	Terminated	State	
SE Delta	Terminated	State	
Slugger	Terminated	State	
Southern Miluveach	Active	State	Brooks Range Petroleum Corporation
Taktuk	Active	Federal	
Tofkat	Terminated	State/Federal	
Tuvaaq	Terminated	State	
Whiskey Gulch	Terminated	State	

* Unit is actively producing oil

Appendix B – General Summary of Applicable Laws and Regulations

Law / Regulation	Level	Year	Relevance
General Mining Act: *30 U.S.C. §§ 22-42*	Federal Law	1872	Legally establishes process and procedure for individuals to make mining claims within the US
Pickett Act: *43 U.S.C. § 141 Stat. 847*	Federal Law	1910 (Repealed 1976)	Authorized the US President to withdraw public lands for preservation underneath the antiquities act (1906)
Minerals Leasing Act: *30 U.S.C. § 181 et. seq.*	Federal Law	1920	Governs process for leasing out mineral rights of US public lands
Alaska State Constitution Article VIII	State of Alaska Constitution	1958	Governs the natural resources and their ownership and management within the State of Alaska
Clean Water Act: *33 U.S.C. §1251 et. seq.*	Federal Law	1972	Establishes open water discharge standards for pollutants to waters of the US
Public Law 94-258	Federal Law	1976	Transfers authority of NPR-4 to the BLM renames it the National Petroleum Reserve-Alaska and allows for public leasing of NPR-A land and mineral rights
30 CFR - 323	Federal Regulation	Implemented in Alaska 1979	Extends permitting authority to the US. Army Corp of Engineers for regulating waters of the US under the Clean Water Act and the Rivers and Harbors Act
Public Law 94-487	Federal Law	1980	Establishes ANILCA to preserve large portions of Alaska State lands
Public Law 115-97 – Title II	Federal Law	2017	Establishes development program for the 1002 area within ANWR